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Key Points:
- Subauroral longitudinally extended emissions are created following intensifications of the poleward boundary and streamer production
- They occur as a separation of east-west bands equatorward from the main oval to the west of the bulge and may be related to STEVE emissions
- They are associated with Subauroral Polarization Streams (SAPS) and Giant Undulations and may be produced by a disruption/overturning of the plasmapause in the SAPS region

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Abstract Observations showing the development of Subauroral Longitudinally Extended Emissions on a global scale are presented. It is demonstrated that they occur as a separation of an east-west arc-like band of luminosity that detaches away from the equatorward edge of the auroral distribution following episodes of auroral streamer production. They persist for time intervals on the order of ∼30 min and devolve into patchy disjointed segments before they fade. Emissions are seen in both 557.7 nm OI and 391.4 nm N₂; 1NG lines, and 630.0 nm emissions are often observed equatorward. The 391.4 nm emissions are typically weaker and fade away more quickly than the 557.7 nm emissions, suggesting that an auroral precipitation source is initially present but is rapidly depleted as the forms age. All cases are associated with enhanced Subauroral Polarization Stream (SAPS) flows, and one event shows clear association with large-scale Giant Undulations (GUs) and the formation of spur-like forms that fold equatorward under the main oval. A model is proposed for the production of subauroral longitudinally extended forms in which nonlinear growth of SAPS-induced surface waves on the plasmapause results in a disruption of the boundary. It is suggested that hot plasma of plasma sheet origin becomes entrained in the plasmasphere to produce transient precipitation-associated auroral emissions that may decay into STEVE emissions and that cold dense plasma from the plasmasphere becomes entrained onto open drift paths to feed long-lived drainage plumes. This process may occur quasi-periodically during intense substorms and storm-time conditions.

1. Introduction

In the phenomenological model of auroral substorm development, first introduced by Akasofu (1964), the ionospheric disturbance begins with a brightening of an arc near the equatorward regions of the auroral distribution in the premidnight sector which can last for up to ∼5 min. Following this initial brightening phase, a rapid poleward motion ensues whereby an auroral “bulge” expands poleward, eastward, and westward to encompass wide sectors of the nightside auroral distribution. The bulge is comprised of intense active auroral bands at its poleward edge and typically develops a westward propagating wave-like “surge” at the westward edge of the poleward boundary (the so-called westward traveling surge [WTS]). There is often a decrease in luminosity below the active poleward boundary with significant structuring equatorward. The expansion phase of the substorm can last ∼0.5–1 h or more until the poleward boundary of the bulge merges with the pre-existing poleward arcs (that likely reside close to the open/closed field line boundary). The intensity and dynamics of the disturbance eventually subsides and recovers to its pre-existing configuration over a time scale of tens of minutes to hours and in the course of the auroral substorm process, other complex types of auroral forms can appear including torches, omega bands and pulsating patches. Over the years, numerous refinements have been made to this schematic, and we now have a very detailed picture of how the auroral substorm develops and how it is related to other types of auroral disturbances.

Perhaps the most important early addition to the Akasofu picture was made by Montbriand (1969, 1971) who was the first to recognize a "previously unnoticed major feature of substorms" that he described as "... the occurrence of small, short-lived, clockwise rotating loops (as seen from above) which form along the PAB [Polar Activated Bands], rapidly orientate into an approximate north-south direction, and quickly degenerate into north-south oriented band segments. These occur between substorm time (ST) 10–15 min” after onset. Montbriand referred to these as North-South Segments (NSS), and they have since been referred...
to by other names including equatorward-diving arcs (Henderson, 1994), NS auroral forms (Henderson et al., 1994; Nakamura et al., 1993), auroral fingers (Liu & Rostoker, 1993; Rostoker et al., 1987), and most recently as auroral streamers. The first studies and characterization of the dynamics of these disturbances on a global scale were made using data acquired with the the Viking/UVI auroral imager launched in 1986 (Anger et al., 1987; Hultqvist, 1987), which was the first global auroral imager capable of taking snapshot style images (whereby every pixel was exposed at the same time; Henderson, 1994, 2012; Henderson et al., 1994; Liu & Rostoker, 1993; Rostoker et al., 1987).

An important finding of the early work is that during the auroral substorm, the bulge typically does not expand smoothly poleward. Instead it often surges poleward in quasi-periodic bursts of activity that recur every ∼5–15 min. Each of these episodes starts with an intensification of the arcs at the poleward edge of the bulge followed by the equatorward ejection of streamers into the bulge. Each intensification is associated with creation of new arcs poleward of the pre-existing arcs. This often resembles a bifurcation of the poleward arc system and the auroral streamers are often (although not always) ejected equatorward from a collapsing (or equatorward-diving) segment of the lower branch. As the streamers descend equatorward, they can start to pulsate (Nakamura et al., 1993), they can distort and even split (Rostoker et al., 1987) as they approach the equatorward regions and can often result in considerable structuring within the otherwise more diffuse appearing equatorward auroras (Forsyth et al., 2020; Henderson, 1994, 2012; Henderson et al., 1994, 2002). In addition, as streamers descend equatorward, they can evolve into auroral torch and omega band structures (Forsyth et al., 2020; Henderson, 2012; Henderson et al., 2002).

Henderson (1994, 2012) and Henderson et al. (1994, 1998) also showed that auroral streamers were associated with substorm injections (and/or the arrival of new particle populations) at geosynchronous orbit and were associated with substorm wedgelet-like positive H-bay ground magnetic perturbations on the ground. Since Bursty Bulk Flows (BBFs) in the tail were discovered at around the same time as the Viking results were emerging and streamers showed similarly bursty/impulsive equatorward-directed behavior, this led to the hypothesis that auroral streamers were an ionospheric manifestation of BBFs in the tail. Numerous subsequent studies have examined the BBF/streamer relationship and confirmed that this hypothesis is likely correct. Perhaps the most convincing of these studies was performed by Nakamura et al. (2001) who showed statistically that the upward field aligned currents associated with auroral streamers maps to the dusk-side of BBFs in the tail which is consistent with their generation via earthward-moving plasma-bubble produced BBFs in the tail (Chen & Wolf, 1993a, 1993b). Another major addition to the auroral substorm picture was made by Henderson et al. (2002) who showed that equatorward moving auroral streamers could evolve directly into auroral torch and omega band forms. Since streamers had already been linked to BBFs in the tail, this provided a new model for omega band formation in which they are produced as a direct consequence of BBFs arriving in the near Earth region. This resolved several poorly understood issues with omega bands including their association with pulsating torch structures, and the fact that the waveforms could be complex with adjacent loops having vastly different “wavelengths.”

Numerous other additions have been made over the years including: the evolution of the bulge toward a “double oval” configuration (Elphinstone et al., 1993; Elphinstone et al., 1995; Henderson, 1994; Kornilov et al., 2016); the occurrence of large-scale coherent spirals or hot-spots along the poleward boundary (Murphy & Johnson, 1996); the occurrence of so-called “contact breakups” at the equatorward region of the bulge as a result of prior streamer activity (Henderson et al., 2002; Nishimura et al., 2010; Oguti, 1973); the occurrence of auroral beading at substorm onset (Donovan et al., 2006; Elphinstone et al., 1995; Henderson, 1994, 2009; Kalmoni et al., 2015; Motoba et al., 2012); the development of periodic substorms and sawtooth events (Belian et al., 1995; Cai et al., 2006; Henderson, 2004; Henderson et al., 2006; Huang et al., 2004; Reeves et al., 2013); the detachment of non-stormtime “SAR arcs” from the main oval during substorm recovery phase (Shiokawa et al., 2009, 2017; Takagi et al., 2018); and the recognition that SMCS/Convection bays can be viewed as substorms that continue to be driven (by reconnection) in a prolonged sense after the bulge has evolved into a double-oval configuration (e.g., Walach & Milan, 2015).

Although many of these additions to the original Akasofu phenomenological model were slow to be adopted in general, many were first recognized decades ago and have since become crucial components of the auroral substorm picture. It is therefore somewhat surprising that in recent years a “completely new,” yet fairly bright, optical substorm-associated phenomenology has been discovered called STEVE (Gallardo-Lacourt
et al., 2018; Gillies et al., 2019; McDonald et al., 2018; Nishimura et al., 2019) that is said to have been completely missed by auroral scientists over the years. Somewhat contrary to this claim, it has been reported that even early auroral scientists like Stormer, may have recognized these displays as distinct (Hunnekuhl & MacDonald, 2020). In addition, there have been a number of observations of various types of subauroral emissions over the past several decades (Frey, 2007), and some of these may also be related to STEVE emissions. In the next few sections, we briefly review these as well as some that may not be related to STEVE (e.g., detached afternoon proton arcs).

1.1. SAR Arcs

Traditionally, SAR arcs are described as relatively featureless east-west aligned broad bands (1–3° in latitude) of faint (usually subvisual) emissions that occur during geomagnetic storms in regions well equatorward of the nominal electron-precipitation-caused auroral oval emissions. These broad arcs can be stable over many hours and unlike typical auroral oval displays, they radiate almost pure atomic oxygen 630.0 nm red line emissions. It is thought that these 630.0 nm SAR arcs are produced where ring current ion populations overlap the plasmasphere and cause heating of ambient F-layer electrons to temperatures sufficient to produce the 630.0 nm red line emission from the excited O(1D) state which has an excitation potential of ∼2 eV (e.g., see Kozyra et al., 1997; Mendillo, Baumgardner, & Wroten, 2016; Rees & Roble, 1975; and references therein). In recent decades, with the deployment of more modern and more sensitive instrumentation, a more detailed description of SAR arcs has emerged and as discussed by Mendillo, Baumgardner, and Wroten (2016), they can actually exhibit a significant range of temporal and spatial variability. From an extensive survey of 314 SAR arc displays observed between 1987 and 2014, they found that: ∼10% persist for >2 nights; ∼10% display a multiplicity of arcs; ∼50% display longitudinal emission variability; ∼40% show associated latitudinally extended emission features; and <5% display deviations from geomagnetic latitude alignment. In addition, they are now detectable quite early during storms where they are seen to begin closer to the oval emissions and can display substantial structuring prior to their southward motion during the main phase. Baumgardner et al. (2007) have also shown that SAR arcs are not always subvisual. In a rare case, they presented observations of an event that reached a brightness of ∼13 kr. In addition, while a defining feature of classical SAR arcs has been the “spectral purity” of the 630.0 nm O(1D) emission line, departures from spectral purity have been reported. Mendillo, Finan, et al. (2016) presented an event in which weaker 557.7 nm patches were co-located with a 630.0 nm SAR arc. In the classical SAR arc excitation theory, it is relatively easy for ring current ions to heat F-layer electrons to temperatures required to overcome the ∼2 eV excitation potential of the 630.0 nm emitting O(1D) state but not at temperatures required to excite the 557.7 nm green line emission. They conclude that precipitation of low energy electrons are responsible for both the 557.7 nm emissions as well as the longitudinal structuring observed in both emissions.

1.2. SAR Arc Detachments

An auroral emission feature that may be closely related to traditional SAR arcs has also been described by (Shiokawa et al., 2009, 2017; Takagi et al., 2018). They show the detachment of auroral arcs from the equatorward portion of the main auroral oval in the premidnight sector (20–22 MLT) at the beginning of substorm recovery phase (even during nonstormtime substorms). They suggest that the detachment of these features may correspond to the dynamical injection of ring current ion populations into the inner magnetosphere at such times. Furthermore, although these detached arc structures are referred to as “SAR arc detachments,” Takagi et al. (2018) point out that while they tend to be dominated by the typical 630.0 nm emissions associated with SAR arcs, in some cases 557.7 nm emissions were also associated with the arcs. They also note that the location and timing of the SAR arc detachments corresponds to the region and timing where enhanced Subauroral Polarization Streams (SAPS) occur. An example showing the development of a similar detached 630.0 nm arc was presented by Henderson et al. (2010) during the November 24, 2001 storm. In their Figure 11, high resolution images from the POLAR/VIS LR camera show the southward progression of a detached 630.0 nm arc in the premidnight sector (with no obvious 391.4 nm emissions). This occurred during an interval of enhanced SAPS flows which were implicated in the production of impressive Giant Undulations (GUs) farther to the west. Although these
types of detached arcs may eventually evolve to become more traditional SAR arcs, as Takagi et al. (2018) point out and as demonstrated by the Henderson et al. (2016) study, additional processes associated with strong SAPS flows may be active during their creation/detachment phase. For example, Sazykin et al. (2002) presented calculations showing that SAPS flows alone can provide enough excitation in the F-region to stimulate substantial additional optical emissions beyond that expected via the traditional ring-current heating mechanism. And a more extensive mechanism involving the formation and excitation of NO in the SAPS region has also been recently implicated in the production of the optical continuum emissions within the mauve-colored STEVE emission feature (Harding et al., 2020).

1.3. Detached Arcs

Detached arcs are east-west aligned, arc-like auroral emissions that have at least one end completely detached equatorward from the nominal auroral oval emissions. These were first discovered in the late 1970s in ISIS-2 auroral imager data (Anger et al., 1978; Moshupi et al., 1977, 1979). They occur on the dusk-side, can extend into the early evening sectors, and are spectroscopically different from SAR arcs in that they emit at both 557.7 and 391.4 nm and relatively little at 630.0 nm. Anger et al. (1978) found that the ratio I(5577)/I(3914) is similar to that found in the diffuse aurora poleward of the arcs, while the ratio I(6300)/I(3914) < 0.1 which is substantially lower than the ratio in the diffuse aurora poleward (where the ratio is ∼0.4 – 0.5). The lower ratio of I(6300)/I(3914) was taken to indicate that the emissions in detached arcs are due to excitation by higher energy particles than in the poleward diffuse auroral region. Direct over-flights of detached arcs were also examined by Wallis et al. (1979) who showed that these structures were consistent with electron precipitation.

1.4. Dayside Detached Proton Arcs

Immel et al. (2002) also examined detached arcs in the dayside afternoon/dusk sector using the IMAGE/FUV instrument together with in-situ FAST overflights and showed that in the cases they examined the detached arcs were almost entirely caused by proton precipitation rather than electron precipitation. From these observations, they conclude that these afternoon/dusk-sector detached proton arcs could be caused by substorm injection of 30 keV protons that subsequently drift to the afternoon sector. Although Immel et al. (2002) suggested that these detached proton arcs are likely the same thing as the detached arcs studied extensively by the ISIS teams in the late 1970s, the precipitation signatures reported in each case are radically different. It is thus quite possible that they are in fact different phenomena. Or it is possible that some of the Moshupi et al. (1979) events are the same phenomena as studied by Immel et al. (2002) and some are not and more work needs to be done in order to sort out this discrepancy.

1.5. Detached Subauroral Patches

Detached subauroral patches are completely detached patches of luminosity that occur equatorward of the auroral oval in the pre-midnight sector (and in a few cases are seen to extend into the early morning sector). They typically have an east-west elongation and can be observed in sets that are irregularly spaced in longitude and can be connected together. As with detached arcs, these features emit in 391.4, 557.7 and 630.0 nm, but are much brighter (Moshupi et al., 1977, 1979). Moshupi et al. (1979) note that I(3914) in patches is ~6 times greater than that for detached arcs and that patch intensities in 557.7 can vary from 1 to 13 kR. In addition, they found that the patches appear to have an origin near the plasmapause and suggested that they may corotate with the Earth (although corotation was not firmly established because motion had to be inferred between passes of the scanning-type imager). Wallis et al. (1979) also concluded that these features were associated with electron precipitation and they proposed a mechanism in which detached blobs of cold plasma (of plasmaspheric origin) became co-mingled with “residual hot plasmaheet” populations resulting from substorm injections. Precipitation into both detached arcs and detached patches would then result from the scattering of electrons due to wave-particle interactions induced by the cold plasma populations. They therefore suggested that the evening detached arcs and patches are related phenomena and represent “atmospheric images” of where detached cold plasma regions existed in the trough region between the inner edge of the electron plasma sheet and the plasmapause. In a more
recent study of detached patches and arc-like forms using GUVI imager data together with DMSP overflights, Zhang et al. (2005) concluded that detached forms were caused by proton precipitation and not electron precipitation. These results were supported by observations of HI (Lyman-α, 121.6 nm) together with the presence of energetic protons and lack of energetic electrons in the DMSP particle data. Despite the lack of precipitating electrons, they suggest a generation mechanism similar to that proposed by Wallis et al. (1979). It is also very interesting to note that Zhang et al. (2005) also find that a number of detached forms were associated with large-scale undulations in the equatorward boundary of the aurora found poleward, and He et al. (2020) have recently shown that such auroral structuring is associated with actual structuring of the equatorial plasmapause. He et al. (2020) also demonstrated that energetic electron and proton populations intrude into the low density regions which could be scattered to produce auroras.

We note that east-west elongated bands of hydrogen emission similar to those discussed above were identified decades ago by Montbriand (1969, 1971) and were included in his updated phenomenological model of auroral substorm development. As shown in Figure 1, which is an annotated version of the Montbriand (1969, 1971) schematic, following the development of auroral streamers east-west bands of subauroral hydrogen emissions separate equatorward away from the oval in the pre-midnight sector (especially below the WTS region).

Montbriand (1969) noted that "during the intense substorm, the occurrence of NSS (auroral streamers) usually results in a breaking away of a portion of the southern part of the hydrogen aura. In (Figure 1e) this is illustrated by two hydrogen associated east-west oriented band segments, or what is referred to (here) as an isolated luminous region of (auroral) hydrogen (ILRH)." Numerous such events were identified by Montbriand in the dusk to midnight sector and he showed that after detachment, they slowly moved equatorward.

Figure 1. Montbriand’s schematic of auroral substorm development. Notable additions to the Akasofu picture include the development of North-South Segments (NSS), equatorward detachment of Isolated Luminous Regions of Hydrogen (ILRH), and simultaneous evolution of hydrogen emission boundaries. The (a) and (b) labels are not alternatives but rather represent the order of occurrence. After Montbriand (1969). ILRH, Isolated Luminous Regions of Hydrogen; NSS, North-South Segments.
He also found cases that rapidly faded and others that persisted for much longer. For the longer-lived cases, he noted that significant intensity fluctuations appeared along the length of the bands. Other emission lines including 557.7 and 630.0 nm appear to be associated with these forms as well. The fact that these were identified as arc-like bands of emissions that detached away from the equatorward part of the oval in association with substorm disturbances indicates that Montbriand’s ILRH features may have been the first modern identification of nightside detached arcs and these in turn may be related to more recent observations of STEVE emissions.

In this study, we examine several cases showing the development of similar Subauroral Longitudinally Extended Emissions as seen from a global auroral imaging perspective, and we confirm that Montbriand’s original association of these structures with poleward boundary intensifications and auroral streamer development is likely correct. We also discuss the possible relationship between these forms and the recently observed STEVE emissions.

2. Observations

We present five examples showing the development of Subauroral Longitudinally Extended Emissions on a global scale that were captured by the Polar/VIS imaging system (Frank et al., 1995) and the DMSP/OLS (Operational Line Scan) imager (Huang et al., 2014). The main instrument used from the Polar/VIS suite is the so-called “Low Resolution” (LR) camera. Despite the name, this is actually the highest resolution camera on Polar. Various filters were used with this imager including the 557.7 nm OI green-line, the 630.0 nm OI red-line, and the 391.4 nm head emission of the $N_2^+$ $1\text{NG}(0-0)$ band system.

2.1. Event 1: ∼06:30 November 9, 1998

This event occurred during a storm on November 9, 1998 and was also recently examined in detail by Henderson et al. (2018). As shown in their Figure 2, the event consists of an explosive brightening of the aurora near the equatorward regions of the auroral oval on the duskside which was preceded by intense equatorward-moving streamer activity farther to the east. As discussed by Henderson et al. (2018), the explosive brightening leaves the equatorward edge of the aurora torn-up and irregular, and there are arc-like segments created that extend below the nominal equatorward edge of the aurora and eventually become detached.

In the Henderson et al. (2018) study, only the green-line images (557.7 nm) from the VIS/LR imager and UV images (130.4 nm) from the VIS/EC (Earth Camera) imager on the Polar spacecraft were shown. In Figure 2, we present additional images acquired at 391.4 and 630.0 nm wavelengths along with the 557.7 nm images. Images at each wavelength are shown using a false color scheme that uses colors similar to the filter wavelength (557.7 nm images use a green color scale, 630.0 nm images use a reddish color scale, and 391.4 nm images use a violet color scale).

As highlighted with annotation in Figure 2, small undulations appear on the equatorward edge of the oval at 06:15:50 UT (green-line image). Then an explosive brightening can be seen in the images taken between 06:18 and 06:21. Following this, the equatorward boundary of the auroral oval in the brightening sector becomes irregular and distorted. By 06:27:39 UT (391.4 nm image), elongated arc-like forms can be seen at subauroral latitudes. After ∼06:30 UT, these forms appear to become isolated detached subauroral arc-like segments. This behavior can be seen in both the 557.7 and 391.4 nm images, but is only obviously present in the 630.0 nm images taken at 06:28:33 and 06:32:09.

Using data from the SSIES and SSJ instruments on the DMSP spacecraft, Henderson et al. (2018) also showed that strong Subauroral Polarization Streams (SAPS) were present during this interval.

2.2. Event 2: ∼10:30 November 9, 1998

This event occurred several hours later during the same storm as Event 1. Although hi-resolution images are available from the Polar VIS/LR camera during this event, none of them cover the duskside region. Fortunately, however, the DMSP F14 satellite passed directly over the region of interest. Figure 3a shows
the visible light image from the DMSP/OLS imager on the F14 satellite which was moving poleward over Russia at the time. The most prominent aspect of this image are the extremely well-defined Giant Undulations (GUs) in the left part of the image far south of the Kara Sea. In addition, farther to the east (south of the Laptev Sea), an elongated arc-like segment can be seen folding under the nominal equatorward edge of the oval. This is very similar to the spur-like structure observed by Polar during Event 1.

Images from the Polar VIS/EC and LR cameras were available for this time period and are shown in Figure 3b together with an overlay of the drift meter data from the SSIES instrument on DMSP/F14. The F14 spacecraft was moving from the lower left to the upper right during this pass and the horizontal flow vectors show the presence of SAPS directly in the region of the undulations and spur-like feature. In Figure 4, data from the SSJ particle instrument are shown together with the east and north component of the magnetic field and the horizontal flow speed. In addition, a rotated version of the the OLS image has been added for
It can be seen that most of the prominent auroral arcs in the OLS image (regions A-D) correspond to inverted V-type electron structures and upward field aligned currents as indicated by negative slopes in the eastward component of the magnetic field. We note that this also includes the spur-like structure that is folding under the oval. The maximum energy associated with the inverted V-structure is 300 eV, however electrons up to a few keV are present in the vicinity of the spur-like auroral feature. In addition, colder electron and ion populations are seen equatorward of the spur. Note that although the center line along the OLS image was traversed nearly linearly in time, the auroral structures do not line up with the SSJ data perfectly. This is because the magnetic footpoint of the F14 spacecraft at ∼850 km geodetic altitude maps poleward of the nadir direction, and the mapping is more distorted at lower latitudes (where the field lines are more significantly out of vertical alignment).

2.3. Event 3: ∼17:40 January 25, 1998

This event occurred at around 17:40 UT January 25, 1998. The Dst index showed only very minor levels of depression during this time which certainly were not strong enough to classify the interval as a storm. Nevertheless, the event occurred during a very intense substorm as shown in the sequence of Polar VIS/LR images presented in Figure 5. The viewing angle from the Polar spacecraft was fairly oblique at this time, looking from the dusk/pre-midnight sector across the auroral oval to the dawn-side limb of the Earth. In the first few frames, an intense and active substorm bulge can be seen with a westward traveling surge. Intense equatorward-moving streamers can be seen up to about 17:45 UT. Starting at about 17:37 UT, the equatorward edge of the premidnight oval begins a dramatic equatorward expansion which leads to the development of a prominent elongated detached subauroral arc-like form. This can be seen in both the 557.7 and 391.4 nm images and is not clearly evident in the 630.0 nm images (which, again, are much noisier than the images at other wavelengths.) Interestingly, at 17:49:23 UT, in 557.7 nm emissions, the arc-like form also appears to split into two arcs although in subsequent frames the arc is not within the field of view of the LR camera.

Figure 6 shows DMSP/SSJ data from F12 and DMSP/SEIS data from F12 and F13. Both DMSP passes were in the southern hemisphere and are plotted together with a Polar/VIS image from the northern hemisphere. The DMSP/F12 drift meter data overlayed on the 17:49:23 UT Polar/VIS image shows a SAPS flow in the region where the detached subauroral feature is located. And, the SSJ data from DMSP/F2 shows the SAPS flows situated well equatorward of the nominal equatorward edge of the electron plasma sheet. We note,
however, that regions between times A and B show some weaker fluxes of low energy electrons and ions and these may be associated with the detached feature.

2.4. Event 4: ~02:40 November 13, 1998

This event occurred during a storm on November 13, 1998, a few days after the one containing Events 1 and 2. This event also shows the separation and detachment of a band of subauroral emissions associated with the development of an intense substorm as shown in Figures 7 and 8. At the beginning of the sequence of images (02:16:35 UT) a substorm surge-like feature can be seen in the eastern part of the nightside oval which indicates the prior development of a substorm farther to the east. Prior VIS/LR and VIS/EC images (not shown) reveal that this substorm was heavily skewed toward the dawn sector.
At around 02:20:11 UT, the equatorward arc in the midnight sector brightens and is followed by a new substorm onset which rapidly expands into an intense active substorm expansion phase bulge. Intense equatorward-moving streamers are observed during this time period particularly emanating from the westward traveling surge region. By around 02:30 UT, the WTS has reached the duskside oval and begins deflecting sunward along its poleward edge there.

By 02:37:24 UT, an elongated subauroral feature begins to separate away from the main oval and this subsequently evolves into an elongated sequence of patchy arc-like segments. This can be seen most prominently in the 557.7 nm images shown in Figure 7 but are also evident in the 391.4 nm images shown in Figure 8. Interestingly, however, a large-scale subauroral region of 630.0 nm emissions can be seen even more equatorward as shown in Figure 9. The extent and stability of this feature may indicate that it is a classical SAR arc.

Figure 5. Development of the northern auroral distribution during the January 25, 1998 storm. A prominent Subauroral Longitudinally Extended Emission feature forms after the westward progression of an intense auroral substorm.
Figure 6. DMSP/SSIES cross-track drift meter data overlaid on POLAR/VIS images (color on the SSIES overlays indicates sunward (orange) or antisunward (blue) flows). The VIS image is from the LR camera at 557.7 nm and shows the northern auroral distribution during the time that the subauroral arc-like feature was observed. The DMSP/SSI electron and ion particle data and the DMSP/SSIES data were obtained during a southern polar region pass. The equatorward edge of the electron plasma sheet is marked and a band of SAPS flows is highlighted.

Figure 7. Development of the northern auroral distribution during the November 13, 1998 storm. All images were taken with the green-line, 557.7 nm filter.
Figure 10 shows OLS and SSIES data from the DMSP/F14 spacecraft for this event. The segmented subauroral feature can be seen in the visible image with a clear substorm surge-like structure stretching from east to west over Canada. The three vertically arrayed spots of city lights seen in the DMSP/OLS image come from Calgary, Red Deer, and Edmonton. A portion of the subauroral feature was therefore situated right over Calgary at this time. The drift meter data from the SSIES instrument shows that SAPS flows were present in the regions adjacent to the detached subauroral emission features.

2.5. **Event 5: ∼17:45 January 13, 1999**

This event occurred on January 13, 1999 during a moderate storm. As shown in Figures 11–13, the formation and evolution of the subauroral arc-like form began 17:42 following an interval of intense streamer...
activity. It evolved into a patchy, subauroral band in 557.7 and 391.4 nm emissions and a more continuous band of emissions slightly equatorward in 630.0 nm emissions.

DMSP F13 and F14 data for this event are presented in Figure 14. SSIES drift meter data from both of the passes overlayed on the northern hemisphere Polar/VIS/LR image were acquired in the southern hemisphere. The SSJ electron and ion data are plotted together with the horizontal velocity measurements in 14a. A clear SAPS flow enhancement can be seen equatorward of the electron plasma sheet and occurred in the location where the subauroral arc-like segment is observed in the Polar VIS data. As with Event 3, some low energy electrons and ions can be seen equatorward of the nominal equatorward edge of the electron plasma sheet, and these may be related to the subauroral feature.

3. Discussion and Conclusions

We have shown several cases in which east-west arc-like bands of luminosity break away from the equatorward edge of the oval following episodes of auroral streamer production. They were seen in both 557.7 and 391.4 nm lines. Although the 630.0 nm images were considerably noisier, several cases presented here showed the presence of these red line emissions, equatorward. In addition, the 391.4 nm emissions appear to be the weakest and tended to decay away more quickly.

The forms are very similar in character to the Isolated Luminous Regions of Hydrogen (ILRH) described many years ago by Montbriand (1969, 1971), and both are likely related to the detached patches (and perhaps some of the nightside detached arcs) studied by Moshupi et al. (1977, 1979) and Wallis et al. (1979) and the non-optically pure SAR arc detachment events reported by Shiokawa et al. (2009); Shiokawa et al. (2017); Takagi et al. (2018).

The global auroral imager data presented here show how these features develop in a global context and in agreement with Montbriand’s schematic (see Figure 1) (inferred from ground-based observations), they tend to form during active substorm times following intervals of poleward boundary activation and intense

![Figure 9](image_url) Subauroral features observed at three different wavelengths (391.4, 557.7, and 630.0 nm). The longitudinally extended detached subauroral features can be seen in the 391.4 and 557.7 nm and 630.0 nm images. The 630.0 nm red-line emission evolve toward a much more extensive and stable subauroral SAR-arc-like emission pattern visible at much lower latitudes.

![Figure 10](image_url) (a) DMSP/OLS visible light image showing detached subauroral arc-like segments. (b) DMSP/SSIES drift meter data plotted on top of a POLAR VIS/LR 557.7 nm image that has been mapped into magnetic coordinates. SAPS flows are evident in the regions occupied by the detached subauroral emissions.
streamer production. Initially, an east-west aligned arc-like band detaches equatorward away from the equatorward edge of the oval in the sector to the west of the bulge (i.e., in the Harang region). As these forms move equatorward and extend eastward, they can develop significant structuring and devolve into patchy disjointed band segments. They persist for time intervals of $\sim 30$ min or so.

We have also demonstrated that these events are associated with enhanced SAPS, and it appears that they can also be related to the development of GUs on the equatorward boundary of the auroral oval in the westward flow region west of the bulge. Although the spatial and temporal resolution of the global imagers are often insufficient to capture the fine structure in this region, two events were associated with the development of a “spur-like” band protruding equatorward of the oval in the SAPS region. We suggest that this activity may be related to a non-linear growth of GU forms in response to streamer-induced SAPS enhancements such that the GUs break (e.g., see Henderson et al. (2018)), resulting in a disruption of the plasmapause. Such activity could be responsible for the detached plasma blobs observed by Chappell (1974).

As with streamer production, such disruptions may occur quasi-periodically during particularly disturbed intervals due to repetitive substorm injections and intense SAPS growth and provide a repetitive source of detached cold-plasma regions co-mingled with hot electrons and ions of plasma-sheet origin across a disrupted segment of the plasmapause. A conceptual model very similar to this was also proposed by Wallis et al. (1979) (see their Figure 7), except that no explicit mechanism for the generation of the detached cold plasma regions was identified. Here, we propose that such detachments may arise naturally via the excitation and non-linear breaking of GUs due to the growth of intense SAPS in the pre-midnight region. Under these conditions, we have all of the ingredients needed for the production of potentially bright

Figure 11. Development of the northern auroral distribution during the January 13, 1999 storm. All images were taken with the green-line 557.7 nm filter. A prominent longitudinally extended subauroral feature develops following intense substorm-associated streamer activity farther to the east.
detached arc-like segments emitting in multiple wavelengths, and such a model may very well explain the detached arcs and plasma patches observed by Anger et al. (1978); Montbriand (1969, 1971); Moshupi et al. (1977, 1979); Wallis et al. (1979).

A conceptual model illustrating these ideas is presented in Figure 15. In (a), hot plasma sheet ions injected across the duskside bulge region excite intense SAPS and GUs. We note that as a consequence of energetic particle drift physics, medium energy ions have direct access to this region of the plasmasphere at all times while electrons (of all energies) do not (unless they are dynamically injected into the plasmasphere by other means). In (b), the GUs grow non-linearly and can break which produces disruption of the plasmapause boundary and an inter-mingling of hot and cold plasma regions. The ion population overlapping the plasmasphere excites a detached SAR arc-like form with possible additional optical emissions due to SAPS-associated thermal heating (e.g., as described by Sazykin et al., 2002 and Harding et al., 2020). It is possible that this mechanism also leads to the entrainment of plasma sheet electron populations which may produce short-lived aurora-like emissions poleward of this arc.

So far we have avoided making an explicit connection between these subauroral detached features and the more recently studied STEVE emissions that have been photographed from the ground. Nevertheless, since both types of features occur in similar regions and under similar conditions, it would be somewhat remarkable to conclude that they are completely unrelated phenomena. To the contrary, it seems more plausible that many of the nightside detached features are related phenomena (especially those occurring during intense SAPS/SAID events) and may even evolve from one to another. For example, the detaching arcs may be the same phenomenon as the IRLH forms discussed by Montbriand (1969, 1971) and the detaching...
SAR-arcs discussed by Shiokawa et al. (2009, 2017) and STEVE emissions as well as traditional SAR arcs (during storms) may be remnants of this activity.

One potential objection to them being related phenomena is that, as pointed out by Mende et al. (2019) and Mende & Turner (2019), there is a lack of significant 427.8 nm emissions in the green-line picket fence structures (in ground observation), and this argues against an auroral electron source of excitation. Conversely, in several of the events presented here, we show that 391.4 nm emissions were present which is not inconsistent with a source of precipitation. However, as we have noted, the 391.4 nm emissions are typically much weaker, less extensive, and tend to decay away more quickly. As well, Nishimura et al. (2019) reported an event that apparently was associated with electron precipitation and in either case, the rapid decay of the 391.4 nm emissions may indicate that a precipitation source may be available early on but decays away relatively quickly after detachment.

Another potential objection to relating these forms to STEVE emissions is that the Mauve arc contains a broader spectrum of continuum emissions. However, since only band-pass filtered images around key emission lines are presented here, we cannot conclude that there were continuum emissions present. On the other hand, as pointed out recently by (Harding et al., 2020), intense SAPS/SAID conditions may be favorable for the production of continuum emissions from excited NO$_2$ molecules and excess red emissions may result from the heating mechanism proposed by Sazykin et al. (2002). Since all of the events presented here were associated with enhanced SAPS flows, it would be surprising and puzzling if this mechanism was not also operative here.

In addition, we note that it is possible that ground-based photography of STEVE emissions could be biased toward capturing the overall phenomenon at a later stage of its life cycle, and this could correspond to times when any transient residual precipitation sources have become exhausted.

Figure 13. Development of the northern auroral distribution during the January, 1999 storm. All images were taken with the red-line 630.0 nm filter. A prominent longitudinally extended subauroral feature develops following intense substorm-associated streamer activity farther to the east.
The conceptual model proposed here and illustrated schematically in Figure 15 may well explain a number of features associated with the development of detached subs-auroral forms over the past several decades, and we suggest that STEVE emissions and more classical SAR arcs (during storms) may be remnants of the detachment process.

In addition to providing a source of plasma sheet particles capable of driving detached subauroral forms potentially with a transient auroral electron precipitation component, the quasi-periodic disruption of the plasmapause would also result in the entrainment of cold dense blobs of plasmaspheric plasma onto open drift paths outside of the nominal plasmapause. We speculate that this population could simultaneously feed so-called long-lived drainage plumes that have been recently observed (Borovsky et al., 2014). Such plumes appear to exist longer than expected based on normal drift times, but the mechanism described here could feed such plumes in an impulsive, quasi-periodic manner over many hours during disturbed intervals.

**Data Availability Statement**

The POLAR/VIS digital data were obtained from the NASA Coordinated Data Analysis Web (CDAWeb) archive at https://cdaweb.gsfc.nasa.gov/pub/data/polar/vis/vis_visible-imager-calibrated/. Data from the SSIES, SSJ, and SSM instruments on the Defense Meteorological Satellite Program (DMSP) satellites were obtained from the National Geophysical Data Center (NGDC) archives located at https://satdat.ngdc.noaa.gov/dmsp/data/. Documentation describing these files is located at https://www.ngdc.noaa.gov/ftp/satellite/dmsp/documentation.html. Data from the DMSP OLS (Optical Line Scan) imager can be obtained from the NGDC (see https://ngdc.noaa.gov/eog/services.html).
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