Relation of Substorm Breakup Arc to other Growth-Phase Auroral Arcs

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Abstract. High-resolution CANOPUS meridian-scanning photometer and all-sky imager observations of pre-onset and expansion-phase auroral arcs are analyzed for expansion-phase onsets that evolve into full substorms and into pseudobreakups. One or more arcs are seen across the sky throughout the growth phase prior to onset. We find that auroral break-up at onset generally does not occur along one of these arcs, contrary to what is currently believed. Instead it generally occurs along a thin break-up arc that forms equatorward of all growth phase arcs a few minutes prior to onset. The intensity of this breakup arc increases monotonically for the few minutes prior to the time normally identified as substorm onset and then typically increases dramatically. These results imply that the processes responsible for substorm onset are not directly related to the formation of growth-phase arcs and that they initiate a few minutes prior to the time normally identified as expansion-phase onset. We also find that arcs poleward of the arc that breaks up appear to be unaffected by substorm onset until expansion-phase auroral activity moves poleward to the location of such arcs. Arcs poleward of the poleward-most extent of pseudobreakup auroral activity show no apparent effects of a pseudobreakup. These observations imply that an expansion phase does not significantly affect the portion of the plasma sheet lying anti-sunward of the field lines having expansion-phase auroral activity until expansion phase activity moves poleward to the field lines of those regions. For pseudobreakups, the observations imply that expansion phase activity never significantly affects plasma sheet regions anti-sunward of the poleward-most extent of field lines having auroral activity. Some pseudobreakups extend only a small distance poleward of their onset location, and the onset of full substorms and of pseudo-breakups appears to be by the same process. Thus our observations imply that the process that initiates the onset of substorms does not require the occurrence of plasma sheet changes, significant enough to affect magnetosphere-ionosphere electrodynamics, along field lines that cross the equator tailward of the substorm onset region.

1. Introduction

It is well known that relatively stable quiet auroral arcs form during the growth phase of substorms. The period of quiet auroral arcs can persist for extended periods of time, occasionally lasting for an hour or more, before a substorm expansion phase is initiated. Since auroral activity reflects the dynamics of the tail plasma sheet, the evolution of quiet auroral arcs before, during, and after substorm onset can give important information on plasma sheet processes associated with onset. However, very little research has been directed toward determining the relation of quiet arcs to the arc that brightens at substorm onset. In the classic paper describing the auroral morphology of a substorm, Akasofu [1964] described the first indication of the expansion phase as “a sudden brightening (within a few minutes) of one of the quiet arcs a few thousand kilometers in length.” He also indicated that major substorms were initiated along the most equatorward quiet auroral arc. These statements have lead to the widespread acceptance (including by the authors of the present paper) that an important aspect of substorms is the breakup of a pre-existing quiet auroral arc that forms during the substorm growth phase. If it indeed is a pre-existing, growth-phase auroral arc that breaks up at substorms onset, then understanding the formation of the quiet arcs is critical for understanding auroral breakup.

Akasofu [1964] further stated that quiet auroral arcs poleward of the one that brightens at onset “remain faint and diffuse until the brightened arc starts to move poleward”. It has been well established that auroral breakup occurs on field lines of the near-Earth plasma sheet that are ~4-6° in latitude equatorward of the poleward boundary of the plasmasheet at their ionospheric end and that cross the equatorial plane at a equatorial radial distance r ~ 6-10 R_E [e.g., Samson et al., 1992]. Thus Akasofu’s [1964] statement about the stability of other growth phase auroral arcs implies that dynamical changes, sufficiently strong to affect magnetosphere-ionosphere coupling, do not occur prior to substorm onset anywhere within the extensive portion of the plasma sheet that lies tailward of auroral breakup field lines. This further implies that substorm expansion phase processes within the plasma sheet do not initiate prior to onset tailward of the auroral breakup field lines. This is true unless such processes could occur without causing an ionospheric signature and without affecting the plasma sheet processes responsible for the formation of quiet arcs, which is highly unlikely. (For example, earthward flow bursts in the plasma sheet have well-established auroral signatures that are not related to substorm onset and which would disrupt quiet auroral arcs [See Lyons, and references therein].) This is contrary to what would be expected from substorm models, such as the near-Earth neutral line model [e.g., McPherron, 1992], which attribute substorm onset to an instability of the $r > 15\text{-}20\ R_E$ plasma sheet.

While several studies imply that substorm onset processes initiate in the inner plasma sheet region of initial auroral brightening [Lyons, 2000, and references therein], it is commonly believed that a process such as neutral line formation in the $r > 15\text{-}20\ R_E$ is generally a fundamental component of substorms, even if such a process is not responsible for expansion phase onset [e.g., Lui, 1991]. However, Akasofu [1964] also stated that "When the substorm is weak the poleward motion lasts for only a few minutes and other arcs may not be seriously affected. Such a substorm results in the pseudo breakup. … The pseudo-breakup is usually associated with a surge which is propagated along a brightened arc, without affecting others." If it is indeed true that arcs poleward of pseudo breakup auroral activity are not affected by pseudo breakups, it would imply that pseudo breakups proceed without significant dynamical changes along plasma sheet field lines that cross the equator tailward of the substorm onset region. Observations [e.g., Koskinen et al., 1993; Ohtani et al., 1993; Voronkov et al., 2000] suggest that the difference between a pseudo breakup and a full onset is their development after onset and that the onset of a pseudo breakup is not distinguishable from the onset of a full substorm. Such observations have led to the conclusion that the onset process for pseudo breakups is the same as for full substorms [Nakamura et al., 1994; Pulkkinen, 1996; Rostoker, 1998]. With this in mind, Akasofu's [1964] results for pseudo-breakups, if generally true, would imply that substorm onset does not require the occurrence of plasma sheet changes, significant enough to affect magnetosphere-ionosphere electrodynamics, along field lines that cross the equator tailward of the substorm onset region. Significant dynamical changes, such as the reconnection of lobe field lines, almost certainly occur and are important during the expansion phase of many full substorms; the implication from Akasofu's results is only that such processes are not a required part of the substorm onset process.

Despite the importance of the above implications of Akasofu's [1964] results, his results have not, to the best of our knowledge, been re-examined with modern instrumentation. Here we do such a reexamination using observations from the high-resolution meridian-scanning photometer (MSP) and all-sky imager (ASI) at the Canadian Auroral Network for the OPEN Program Unified Study (CANOPUS) station Gillam (GILL) located in central Canada at a geomagnetic latitude $\Lambda = 67°$. Our results are in agreement with Akasofu's conclusions regarding the stability of other arcs before onset and throughout pseudobreakup events, giving support for the implications described above that are related to these conclusions. However, we find the Akasofu's conclusion regarding the brightening of a pre-existing quiet auroral arc at expansion phase onset requires significant modification that is important for understanding substorm onset.

2. Observations

We have examined the MSP and ASI data from Gillam for 1996 and 1997 and found 11 onsets for which viewing conditions at Gillam were clear, good MSP and ASI data are available, and for which breakup and the arc along which breakup occurred were within the field of view of the ASI. Four of these onsets were full substorms, which we define as onsets followed by active expansion-phase aurora that moved poleward to near the poleward boundary of the auroral oval, and seven of these onsets were pseudobreakups. For all the pseudobreakups, the region of active expansion phase aurora did not move poleward of the field of view of the Gillam ASI. The dates and UT's of the 11 onsets are given in Table 1, and each onset is labeled as either a full onset (F) or a pseudobreakup (P).

Table 1: Dates and times of breakup arc formation (Formation UT) and of onset (Breakup UT) for full (F) and pseudobreakup (P) substorm events used in this study

Date	Type	Formation UT	Breakup UT
96/01/18*	F	0454	0459
96/02/12	P	0242	0245
96/02/19*	F	0347	0352
96/04/11*	P	0323	0331
96/04/11*	P	0346	0348
96/04/13	P	?	0415
96/05/11*	P	0416	0420
97/01/29	F	0423	0427
97/02/02	F	0507	0512
97/02/27	P	0317	0321
97/10/07	P	?	0530

Figures 1A-D show summary plots of the MSP data and ground magnetometer for four 1 hr intervals that include the five onsets marked with an asterisk in Table 1(two of the onsets are included in panel D). The upper panel in each Figure gives keograms of the 5577 Å emissions observed by the Gillam MSP as a function of Λ and UT. These emissions result primarily from the precipitation of $\gtrsim 1$ keV electrons, and their observation identifies auroral arcs and disturbances that result from the precipitation of accelerated electrons. Intensities measured along the magnetic meridian as a function of elevation angle have been converted to intensities as a function of Λ by assuming a fixed height of 110 km for the emissions. The intensity scale of each keogram has been adjusted to emphasize the emission enhancement near the time of the onsets. Also shown in each figure are Pi2 and Z-component magnetic field observations from Gillam, X-component ground magnetometer data from stations along the Gillam magnetic meridian, and X-component magnetograms from Poste-de-la-Baleine (PBQ) and Rabbit Lake (RABB) located at approximately the same Λ as Gillam, but ~1.5 and ~1 hr in MLT to the east and west of Gillam, respectively. The stations along the Gillam meridian are, from high to low latitude, Rankin Inlet (RANK), Eskimo Point (ESKI), Fort Churchill (FCHU), Gillam (GILL), and Island Lake (ISLL). Solid vertical lines in each figure identify substorm onset times. The onsets in Figures 1A and 1B were of full substorms, and those in Figures 1C and 1D were of pseudobreakups. Onset times where identified using the data in Figure 1 and the Gillam all-sky imager data and are accurate to ~1 min.

The first example (Figure 1A) shows a substorm at 0459 UT on January 18, 1996, an event that has also been studied by Friedrich et al. [2001]. Auroral brightening occurred at $\Lambda \approx 67°$ at that time and was followed by poleward expansion of the region of brightened aurora. The onset was accompanied by X-component Pi2 pulsations and a decrease in the Z-component at Gillam. The decrease in the Z-component indicates that electrojet formation at onset was centered poleward of Gillam. A maximum perturbation in the ground X-component of ~-700 nT was observed at ESKI ($\Lambda \approx 72°$) 23 min after onset. The magnetometer data from PBQ and RABB show no evidence for substorm activity initiating prior to 0459 UT.

Two-dimensional images of 5577 Å emissions from the Gillam ASI for the period near the 0459 UT onset are shown in Figure 2A at 1 min intervals, except for a data gap from 0501-0503 UT. North is to the top and east is to the right in each image. A grid of magnetic latitude and longitude at 2° intervals in overlaid on the first image, the red horizontal and vertical lines indicating 67° latitude and 330° longitude respectively. The image intensity scales have been adjusted to emphasize the relatively low auroral intensities prior to and at onset.

The images in Figure 2A show a series of arcs during the growth phase prior to onset, which are identified on the 0453 UT image. The initiation of auroral breakup can clearly be seen in the 0459 UT image. Looking at the images prior to breakup shows that breakup did not occur along one of the pre-existing quiet auroral arcs. Instead it occurred along a new auroral arc that formed just equatorward of the equatorward-most growth phase arc. This new arc, which we refer to as the “breakup arc”, can first be identified in the 0455 UT image. It can be seen from Figure 1A that this arc formed before any of the ground signatures of substorm onset. The arc first appeared as a narrow east-west oriented arc. It then grew in intensity until breakup, after which the arc became highly distorted. Also, notice that the growth phase arcs were not significantly affected by the appearance of the breakup arc, and that the growth phase arcs maintained their integrity until expansion phase activity moved poleward to the location of individual arcs. There does, however, seem to have been some decrease in the intensity of the growth phase arcs near the time of breakup.

Figure 3A shows line plots of the Gillam MSP observations of 5577 Å emissions. Emission intensities are plotted as a function of elevation from the most equatorward looking direction to the most poleward looking direction. Line plots are shown for every 30 s from 0430 to 0501:30 UT and stacked vertically with increasing time. Thin dashed lines are drawn through intensity peaks to indicate the location of the growth-phase arcs. These arcs appear to form and fade away over a time scale of ~10-15 min. The breakup arc is identified with a heavy dashed line. This arc can be seen to be a new arc that forms equatorward of all growth phase arcs, consistent with what is seen in the ASI images. This arc is first identifiable in the MSP line plots at 0454:30 UT, 4.5 min prior to onset, and can be seen to have a peak intensity that monotonically increases with time until breakup. The stability of the growth phase arcs as the breakup arc forms and grows can also be clearly seen in the MSP data until the breakup emissions overwhelm the emissions from the growth-phase arcs. This example seems to show a sequence of new arcs forming equatorward of previously formed arcs during the substorm growth phase prior to formation of the breakup arc; this behavior, however, is not commonly seen in the cases we have examined.

Observations from a second example, a relatively localized substorm [see also Voronkov et al. [2002]) with an onset at 0352 UT on February 19, 1996 are shown in Figures 1B, 2B, and 3B. The onset is clearly seen in the Gillam Pi2s and at $\Lambda \approx 67°$ in the Gillam MSP (Figure 1B). Electrojet formation was again centered poleward of Gillam, and a maximum perturbation in the ground X-component of ~-160 nT was observed at FCHU 33 min after onset. The magnetometer data from PBQ and RABB show no evidence for substorm activity initiating prior to ~0352 UT at longitudes ~1.5 hr to the east and ~1 hr to the west of Gillam. The ASI images (Figure 2B) show very weak growth phase arcs. At 0347 UT, a thin breakup arc can first be identified equatorward of all the growth phase arcs, and this arc then increased in intensity until onset. Auroral breakup in this case is first seen at 0353 UT along the westernmost portion of the breakup arc, and the growth phase arcs appear unaffected by the formation, increase in intensity, and initial breakup of the breakup arc. It is difficult to identify the very weak growth phase arcs in the line plots of the MSP 5577 Å data, but growth phase arcs can marginally be seen by blowing up and expanding the vertical scale (Figure 3B). In Figure 3B, the breakup arc can first be discerned at 0350 UT and can be seen to then grow in intensity monotonically prior to onset. As in Figure 3A, Figure 3B shows that the breakup arc formed equatorward of the growth phase arcs and the growth phase arcs appear to not have been affected by the formation and growth of the breakup arc.

Observations from a pseudobreakup with onset at 0420 UT on May 11, 1996 are shown in Figures 1C, 2C, and 3C. The ground magnetic signatures of this pseudobreakup are weak; however the auroral enhancement of the onset shows clearly in the MSP (Figure 1C) and ASI (Figure 2C) observations. As with the two substorm onsets discussed above, the ASI data show that the auroral brightening associated with this onset did not occur along one of the pre-existing quiet auroral arc. Instead it occurred along a new auroral arc that formed equatorward of the growth arcs and that can first be discerned at 0416 UT. The arc then increased in intensity before beginning to expand poleward at 0420 UT. The formation of this new breakup arc equatorward of the other arcs and its growth show clearly in the MSP line plots (Figure 3C). Again, the more poleward arcs do not appear to have been significantly affected by the formation and growth of the breakup arc.

The final two examples of pseudo breakups are onsets at 0331 UT and 0348 UT on April 11, 1996. Observations for these are shown in Figures 1D, 2D, and 3D. Both onsets can be seen in the MSP data in Figure 1D. The first one was quite weak and had only very weak ground magnetic effects. The second onset was stronger and was associated with ~50 nT ground magnetic perturbations at GILL and PBQ as well as enhanced Pi2 pulsations at GILL. ASI images are shown in Figure 2D for the 0348 UT onset. There were a series of growth phase arcs prior to onset. Formation of the breakup arc became discernable at 0346 UT, again just equatorward of the equatorward-most growth phase arcs. The breakup activity began to expand poleward, but never moved poleward of the center of the ASI field of view. The more poleward growth phase arcs again did not show affects associated with by the formation and growth of the breakup arc. Those poleward of the poleward most extent of the breakup activity maintained their integrity throughout the duration of the pseudobreakup, though they did decrease in intensity after onsetfrom 0350-0352 UT.

Line plots of the MSP data for April 11, 1996 are shown in Figure 3D and the two pseudobreakups can be seen. The spatial separation of the breakup arc and subsequent expansion phase activity from the more poleward arcs can be clearly seen for these pseudobreakups and is particularly dramatic throughout the period of the 0331 UT pseudobreakup. Also, as with the previous examples, the poleward arcs show no indication of being significantly affected by the expansion phase activity, implying a separation between the processes responsible for the poleward arcs and those responsible for the pseudo breakup.

3. Summary of observations for all events.

For all 11 events that we have examined, there were one or more arcs throughout the growth phase prior to onset. For 9 of these events, we were able to determine that auroral breakup occurred along a new, thin auroral arc that formed equatorward of all the pre-existing growth phase arcs and not along one of the pre-existing arcs. For the other two events, the data was ambiguous as to whether onset occurred along a new arc or along the equatorward-most growth-phase arc. This could be because the new arc formed too close to the equatorward-most growth phase arc for the distinction between the two arcs to be clearly resolved, but it is also consistent with the possibility that some onsets do not occur along a new arc. For the 9 cases where identification of the new arc was clear, the breakup arc first became observable 2 to 8 min prior to onset. In nearly all of these cases, the intensity of the breakup arc increased monotonically prior to and after onset. The only exception was prior to the 0331 UT onset on April 11, 1996, when the intensity increased for a few min and then decreased before increasing again prior to breakup. The ASI images for this case (not shown) suggest there may have been a very small pseudo-breakup at 0227 UT, leading to the lack of a monotonic intensity increase prior to onset and a relatively long time (3 min longer than for any other case) between first detection of the breakup arc and onset.

We have also examined the evolution of the growth phase auroral arcs at and after onset. After onset, active expansion phase aurora expands poleward. We have found that, in general, auroral arcs poleward of the substorm breakup arc do not show significant effects of breakup until the poleward extending expansion phase auroral activity reaches these arcs. Arcs that remain poleward of the poleward-most extent of pseudo breakup activity are found to not show significant effects of pseudo breakups. We have noticed a reduction in intensity of growth-phase arcs near the time of onset on a few occasions, but we have not determined whether or not this is a change related to onset.

3. Conclusions

The observations analyzed here show that significant modification is needed to one of the many important conclusions reached by Akasofu [1964]. Specifically, we have found that auroral breakup does not generally occur along a pre-existing quiet auroral arc that forms during the substorm growth phase. Instead it, at least often, occurs along a new auroral arc, referred to here as the breakup arc, that forms equatorward of all pre-existing growth phase arcs. It is possible that breakup always occurs along such a new arc, but if this is the case, then the breakup arc sometimes forms too close to the equatorward-most growth phase arc for the two arcs to be definitively distinguished. The observation that breakup occurs along a new arc implies that the processes responsible for substorm onset are not directly related to the formation of growth-phase arcs.

We have also found that the breakup arc generally becomes discernible ~4-5 min before expansion-phase onset and grows in intensity monotonically until breakup. The arc intensity then generally grows explosively and its shape becomes distorted. This implies that the processes responsible for expansion-phase onset initiate on breakup field lines ~4-5 min prior to the time normally identified as onset, and it is consistent with an instability that grows exponentially prior to onset and leads to nonlinear vortex formation and expansion [e.g., Voronkov et al., 2000]. A time delay between the initiation of expansion phase processes and substorm onset on the ground that is approximately the same as found here has also been inferred to occur near the equatorial plane from CRRES spacecraft observations of the inner plasma sheet [Erickson et al., 2000].

Our analysis of the evolution of the growth phase auroral arcs at and after onset has given results consistent with the conclusions of Akasofu [1964] regarding arcs poleward of the breakup arc. Specifically, we have found that such arcs are not significantly affected by breakup until expansion-phase activity moves poleward to the location of the arcs. This implies that dynamical changes within the plasma sheet that are significant enough to affect magnetosphere-ionosphere coupling move tailward from onset field lines with the active aurora, and that such changes do not occur prior to substorm onset tailward of the onset field line region. We have also found that arcs poleward of the poleward-most extension of expansion-phase auroral activity during pseudo-breakups appear to never be significantly affected by pseudo-breakup processes. Previous studies have suggested that the same process initiates onset for both pseudo breakups and for full substorms. If this is the case, then our results imply that the substorm onset process does not require that significant changes, such as an onset of reconnection, occur within the plasma sheet tailward of the field line region of auroral breakup.

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Figures

Figure 1. Summary plots of the MSP data and ground magnetometer for four 1-hr intervals that include the five onsets used as examples in this paper. For each 1 hr interval, the upper panel gives a keogram of the 5577 Å emission intensities observed by the Gillam MSP as function of Λ and UT. The intensity scale of the keograms has been adjusted to emphasize the emission enhancement near the time of the onsets, which are identified by thick vertical lines for each onset. Vertical dashed lines identify the times when the breakup arc first became discernible.

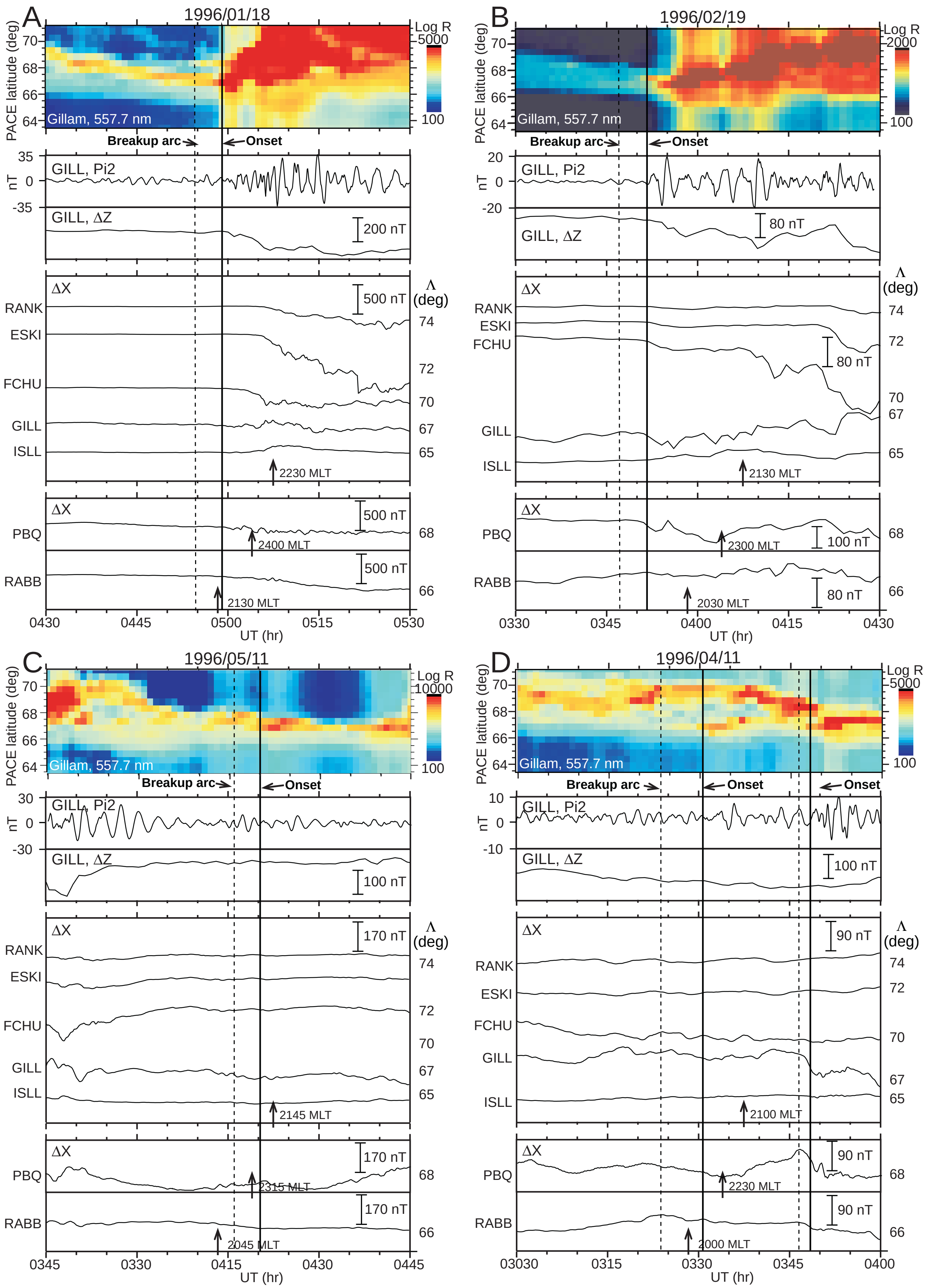
Figure 2. Two-dimensional images of 5577 Å emissions from the Gillam ASI for periods surrounding four of the onsets shown in Figure 1. North is to the top and east is to the right in each image. A grid of magnetic latitude and longitude at 2° intervals in overlaid on the first image, the red horizontal and vertical lines indicating 67° latitude and 330° longitude respectively. The image intensity scales have been adjusted to emphasis the relatively low auroral intensities prior to and at onset. In Figure 2B, the intensity scale was changed at 0352 and 0358 UT; the intensity scale in the figure applies to the images before 0352 UT.

Figure 3A. Line plots of the Gillam MSP observations of 5577 Å emission intensities as a function of elevation angle from the most equatorward looking direction to the most poleward looking direction. Lines are shown for observations taken every 30 s from 0430 to 0501:30 UT on January 18, 1996 and are stacked vertically with increasing time. Thin dashed lines are drawn through intensity peaks to indicate the location of growth-phase arcs. The breakup arc is identified with a heavy dashed line.

Figure 3B. Same as Figure 3A, except observations are shown for 0344 to 0358 UT on February 19, 1996.

Figure 3C. Same as Figure 3A, except observations are shown for 0400 to 0423 UT on May 11, 1996.

Figure 3D. Same as Figure 3A, except observations are shown for 0310 to 0400 UT on April 11, 1996 and the time interval shown includes two onsets.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Breakup arc
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RANK
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FCHU
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Gillam, 557.7 nm
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Breakup arc
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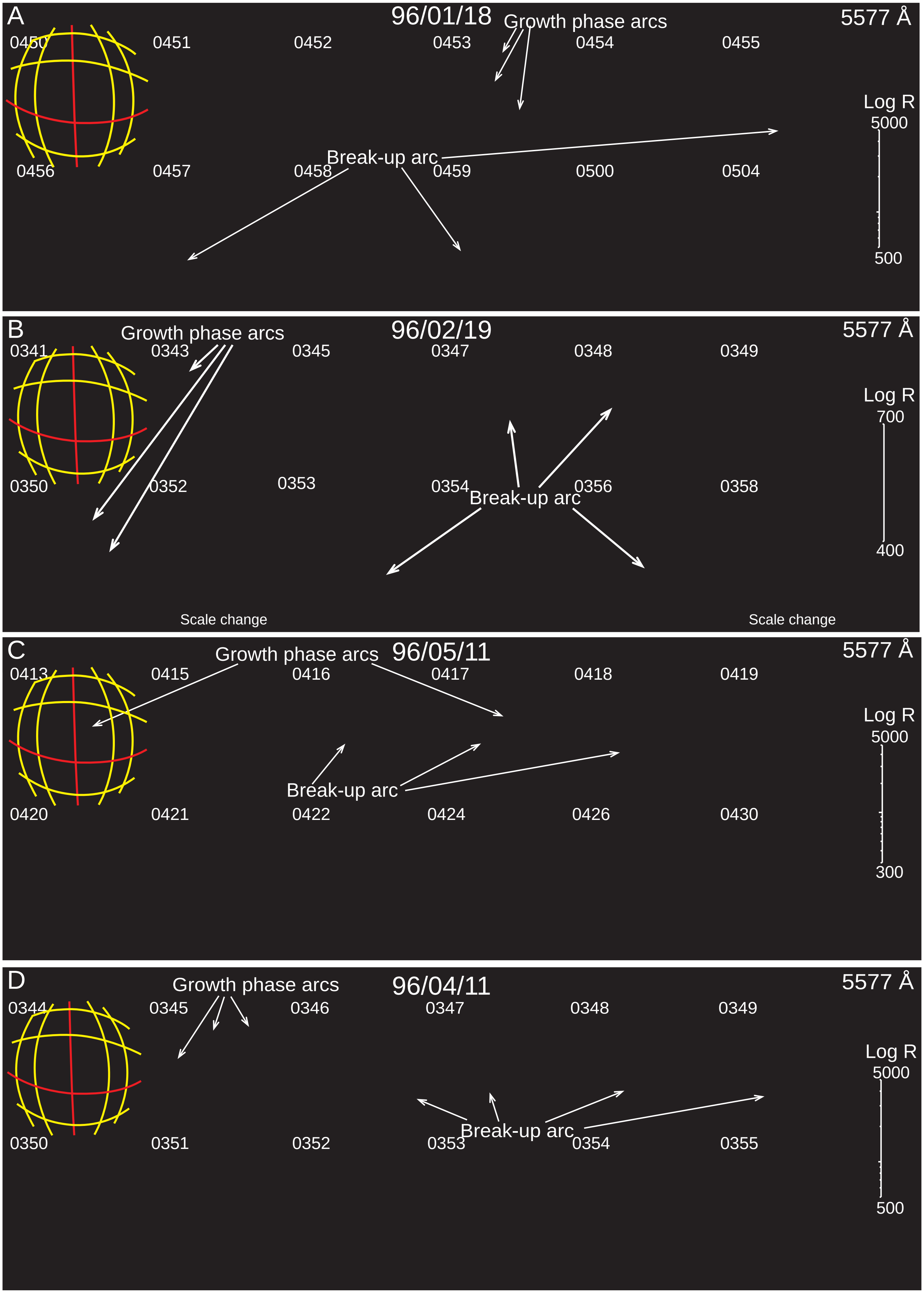
Figure 1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96/01/18
Growth phase arcs
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Log R
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Break-up arc
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Growth phase arcs
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Break-up arc
0356
0358
400
Scale change
Scale change
C
Growth phase arcs
96/05/11
5577 Å
0413
0415
0416
0417
0418
0419
Log R
5000
Break-up arc
0420
0421
0422
0424
0426
0430
300
D
Growth phase arcs
96/04/11
5577 Å
0344
0345
0346
0347
0348
0349
Log R
5000
Break-up arc
0350
0351
0352
0353
0354
0355
500

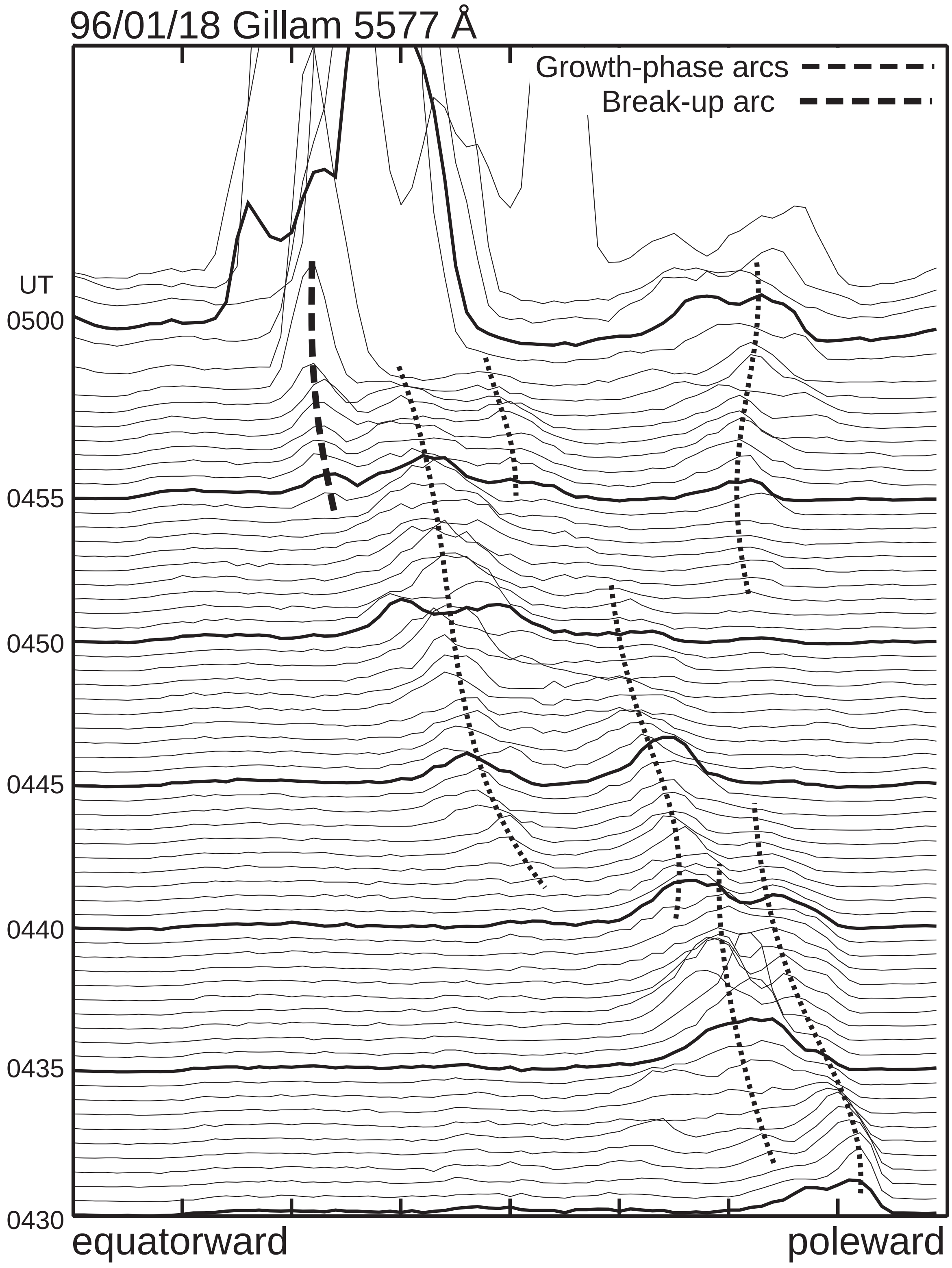
96/01/18 Gillam 5577 Å
Growth-phase arcs
Break-up arc
UT
0500
0455
0450
0445
0440
0435
0430
equatorward
poleward

Figure 3A

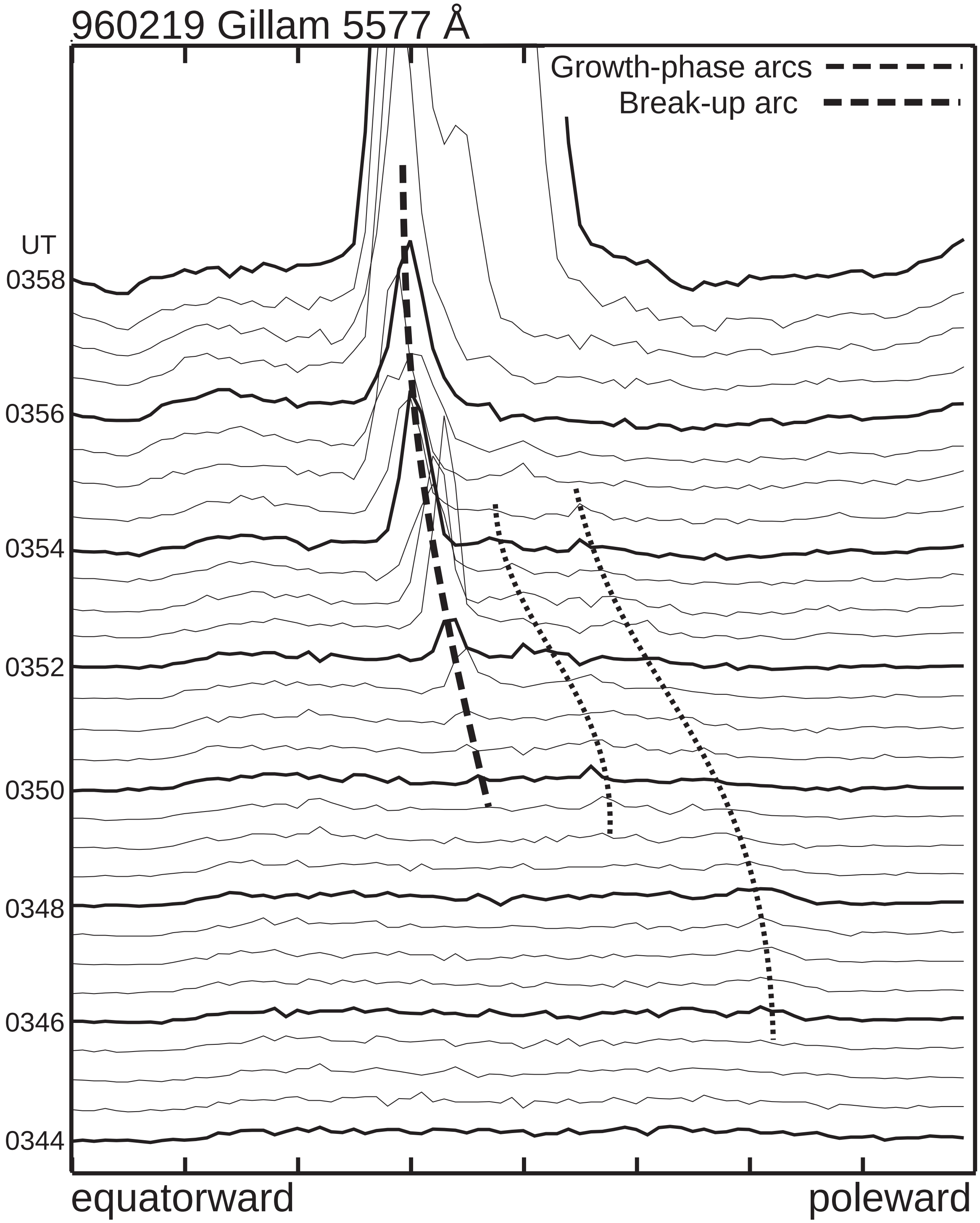
960219 Gillam 5577 Å
Growth-phase arcs
Break-up arc
UT
0358
0356
0354
0352
0350
0348
0346
0344
equatorward
poleward

Figure 3B

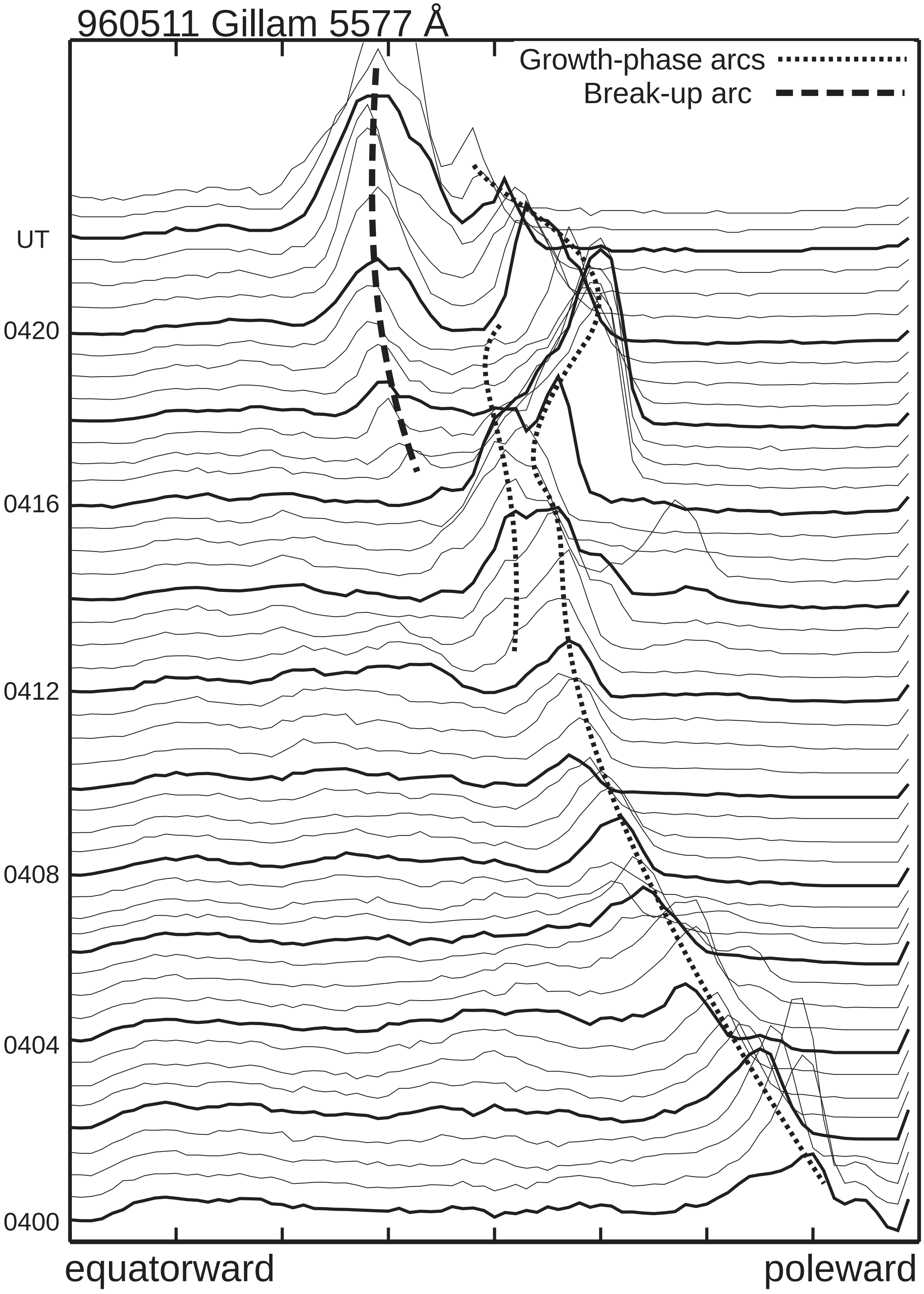
960511 Gillam 5577 Å
Growth-phase arcs
Break-up arc
UT
0420
0416
0412
0408
0404
0400
equatorward
poleward

Figure 3C

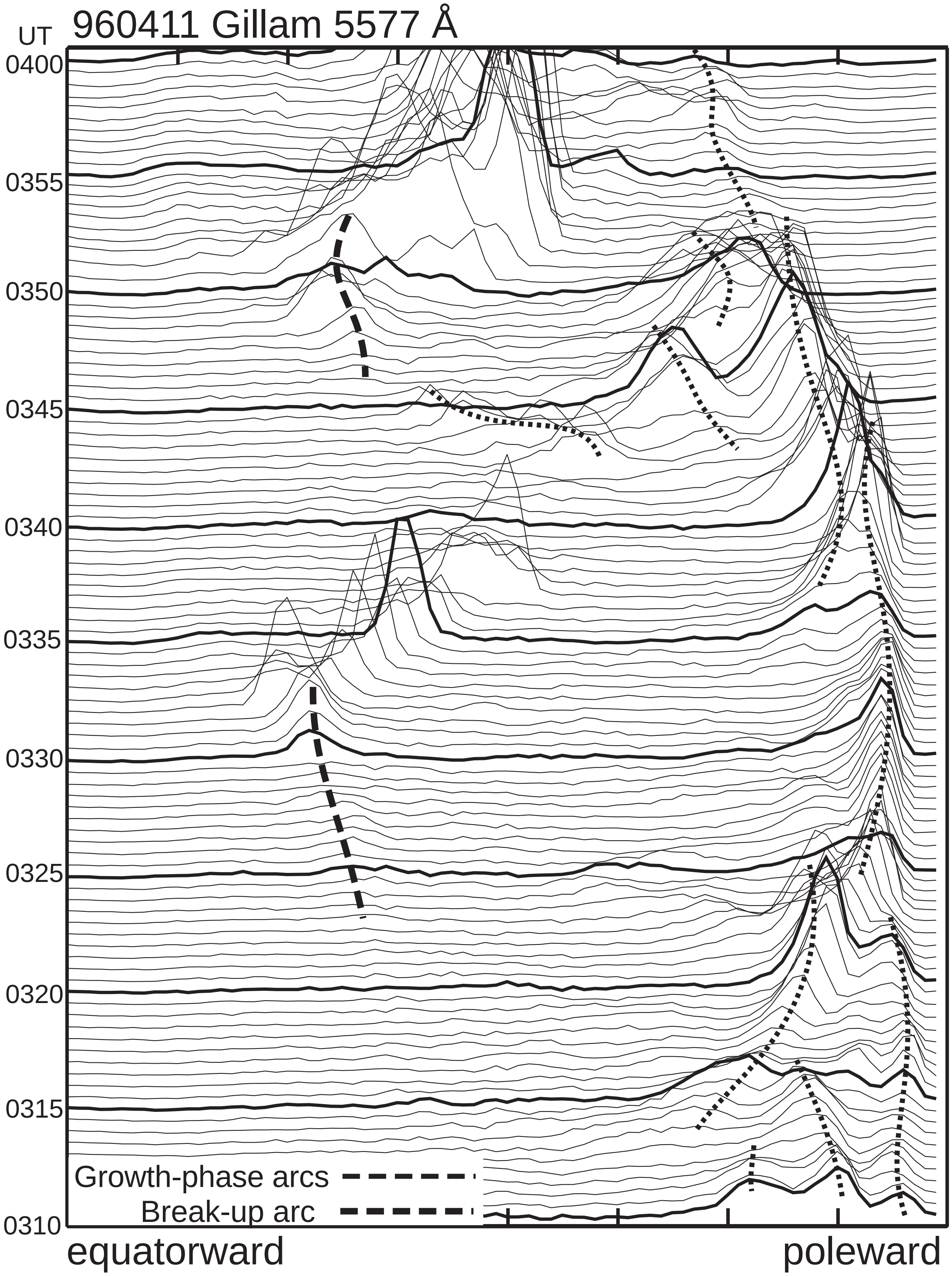
960411 Gillam 5577 Å
UT
0400
0355
0350
0345
0340
0335
0330
0325
0320
0315
0310
Growth-phase arcs
Break-up arc
equatorward
poleward

Figure 3D