Statistical significance of association between whistler-mode chorus enhancements and enhanced convection periods during high-speed streams

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[1] During high-speed solar wind streams, substorms occur repetitively and relativistic electron fluxes enhance significantly. It has recently been proposed that enhanced dawnside chorus waves lead to the energization of the relativistic electrons and that they are associated with the periods of enhanced convection that precede substorm expansions, rather than with the expansions themselves. In this paper, we have evaluated the statistical significance of this association using a total of 657 substorms during high-speed solar wind streams observed by the ACE spacecraft and whistler-mode chorus waves observed from the VLF/ELF Logger Experiment (VELOX) at Halley station, Antarctica. We find that ~66% of the substorm events identified at 0400–1400 MLT show the association with the chorus enhancement that starts to increase ~35 min, on average, prior to substorm onsets and remains elevated until declining back to near the preenhancement level in ~16 min, on average, after substorm onsets. Our statistical results suggest that a large number of the chorus wave enhancements at dawn to postnoon local times occur during the enhanced convection period of the substorm growth phase. This is distinguished from the chorus wave enhancement near midnight that is caused by substorm-injected electrons after onsets. We find that ~59% of the events identified at 2200–0200 MLT show chorus enhancements that start on average ~6 min after substorm onsets and remain elevated for ~32 min on average.

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1. Introduction

[2] The relativistic electron flux of the Earth's radiation belt often increases substantially. *Li et al.* [1997a] have shown that the phase-space density of source electrons in the solar wind is too low to account for the observed flux increase of relativistic electrons. Thus the authors ruled out this external source as a cause for the relativistic electron increases within the inner magnetosphere. Another possibility of the relativistic electron flux enhancement is internal acceleration within the magnetosphere, and a few candidate mechanisms have been proposed.

[3] One candidate is that by ULF waves. *Rostoker et al.* [1998] reported that relativistic electron enhancement events are well associated with enhanced ULF power. A similar result was reported by *O'Brien et al.* [2001]. *Liu et al.* [1999] suggested that magnetic pumping by ULF waves can lead to the observed high relative electron flux in a time as short as a few hours under parameters appropriate for magnetic storms. Inward radial diffusion, enhanced by ULF waves, can also provide an important mechanism for acceleration [e.g., *Schulz and Lanzerotti*, 1974; *Mathie and Mann*, 2000; *Mann et al.*, 2004]. However, radial diffusion may not account for the flux increases in the heart of the radiation belt near L = 4 where the phase space density has been found to peak [*Selesnick and Blake*, 2000; *Green and Kivelson*, 2004]. This and other reasons such as relatively long timescales for inward radial transport [*Miyoshi et al.*, 2003] and flat-topped pitch angle distributions [*Horne et al.*, 2003a] seem to suggest the necessity for a local acceleration process [*Chen et al.*, 2006; *Iles et al.*, 2006; *Shprits and Thorne*, 2004]. In particular, the flat-topped pitch angle distributions are energy-dependent, which is observational evidence of electron-chorus interactions. There has been a suggestion that relativistic electron peaks near L = 4–5 are likely by VLF/ELF acceleration whereas ULF activity is probably dominant at geosynchronous orbit and beyond [e.g., *O'Brien et al.*, 2003]. It has

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been proposed that resonant interactions with whistler-mode chorus waves can be an important mechanism for electron acceleration from energies near 100 keV to above 1 MeV in the region outside the plasmapause [*Temerin et al.*, 1994; *Li et al.*, 1997b; *Summers et al.*, 1998, 2002; *Horne et al.*, 2003b; *Horne and Thorne*, 2003]. Spacecraft observations such as those by CRRES [*Brautigam and Albert*, 2000; *Meredith et al.*, 2001, 2002], POLAR [*Hwang et al.*, 2004], and EXOS-D [*Miyoshi et al.*, 2003] indicate the necessity of local acceleration by whistler chorus. Whistler chorus observations have also been available from ground stations such as those at Halley station in Antarctica as reported in several papers by *Smith* [1995] and *Smith et al.* [1999, 2004a, 2004b]. The average intensities of chorus were found to be larger for storms with relativistic electron flux enhancements than for those without such an enhancement [*Smith et al.*, 2004b].

[4] The minimum energy of electrons in the seed population that can resonate with whistler chorus is typical of the plasmas sheet electrons distribution. *Meredith et al.* [2001, 2002] suggested that the gradual acceleration of electrons to relativistic energies is possible in the presence of prolonged substorm activity that produces enhanced subrelativistic injected electrons and enhanced chorus waves. In fact, *Smith et al.* [1999], using the ELF/VLF wave data at Halley ground station in Antarctica, reported that chorus enhancements near midnight are an unambiguous signature of the substorm expansion phase. However, what is more relevant to relativistic electron flux enhancements is enhanced chorus waves in the dawn to noon region, where electrons that excite chorus waves can be supplied by transport from the plasma sheet under enhanced convection combined with dawnward magnetic drift. *Meredith et al.* [2003] reported that the most favorable condition for electron acceleration to relativistic energies by whistler chorus waves occur during active conditions in the region $4 < L < 6$ between 0300 and 1000 MLT outside the plasmapause for equatorial chorus. For the midlatitude region, they reported that favorable conditions for electron acceleration by chorus waves occur at 0600–1400 MLT. *Smith et al.* [2004a] also reported that the storm chorus enhancement maximizes at postdawn local times. A similar result was included in the work by *O'Brien et al.* [2003].

[5] Recently, *Lyons et al.* [2005] reported several examples to suggest that it is the enhanced convection period preceding the substorm onset, rather than the substorm expansion phase, that is associated with the dawnside chorus enhancement, which is expected to accelerate seed electrons to MeV energies. The main idea was based on the fact that a period of enhanced convection for at least ∼25 min (the typical minimum time required for a substorm growth phase) is expected prior to substorm onsets, which can bring electrons toward the dawnside around the Earth, and significant reductions in the strength of convection lead to substorms [*Lyons et al.*, 2003, and references therein] which can decrease the source electron supply. Therefore chorus intensities are expected to be most intense during growth phase periods prior to onset and to decrease after onset within the timescale it takes for plasma sheet electrons to drift away from the dawnside regions (∼15–30 min). The examples presented by *Lyons et al.* [2005] clearly support this idea. Also as pointed out above, this is distinguished from the chorus near midnight, which is preceded by the substorm onset and is most likely due to the direct injection of electrons during the substorm expansion phase [*Smith et al.*, 1999].

[6] In the present work, we extend *Lyons et al.*'s [2005] work by using a large number of events to determine the statistical significance of the proposed idea. While *Lyons et al.* [2005] studied events during seven days of high-speed stream intervals in November 2003, we examine far more events during nearly all high-speed stream intervals in the second half of 2003. The high-speed streams are of particular importance since they are the periods that are characterized by repetitive substorms, enhanced chorus activity, and relativistic electron flux enhancements [*Summers and Ma*, 2000], and this relationship is the main subject of the present paper. We perform more comprehensive analysis of the relationship than done in the previous paper by *Lyons et al.* [2005].

2. Data and Methodology

[7] Figure 1 shows the solar wind speed V_{sw} (black line), the solar wind number density N_{sw} (wine line), and the IMF Bz (blue line) observed by ACE for July through December 2003. It also shows the geosynchronous >2 MeV electron flux observed by GOES 10 (red line). This period is characterized by a series of multiday high-speed solar wind streams having speeds up to 800 km/s. Each stream is preceded by a compressional region of enhanced N_{sw}. The IMF shows continuous Alfvénic fluctuations during the high-speed streams. Under such solar wind conditions, substorms occur repetitively [e.g., *Tsurutani et al.*, 2006]. Recently, *Lee et al.* [2006] showed that a northward turning of the Alfvénic IMF fluctuations preceded by a moderately southward IMF Bz leads to a significant fraction of substorm onsets. As it can be seen in Figure 1, the relativistic electron flux increases substantially during those high-speed stream intervals, often preceded by a large flux dropout that could be due to the preceding enhanced solar wind density leading to magnetopause shielding of geosynchronous particle drifts orbits. More discussion can be found in the paper by *Lyons et al.* [2005]. In our statistical study, we use events that occurred during these high-speed streams, and the gray-hatched boxes in Figure 1 indicate the specific intervals that we have examined for the present study.

[8] First, we have identified the substorms during the indicated intervals using the geosynchronous energetic particle flux data at energies from 50 to 350 keV for electrons and 50 to 400 keV for protons as measured by LANL spacecraft and the ground magnetic H-component data at low to middle latitudes. The substorm onset time is determined based on the particle injection near midnight and the nightside positive H bay, which are two of the main indicators of substorm onsets. In this study, we use 1 min time resolution particle flux data from the LANL spacecraft and consider injection events for which at least one LANL spacecraft covers the near-midnight region so that the quasi-dispersionless injection signature can be identified within the 1 min time resolution. Then we examine the association of the identified substorms with chorus enhancements.

[9] To evaluate the chorus activity, we use whistler-mode wave observations from the VLF/ELF Logger Experiment

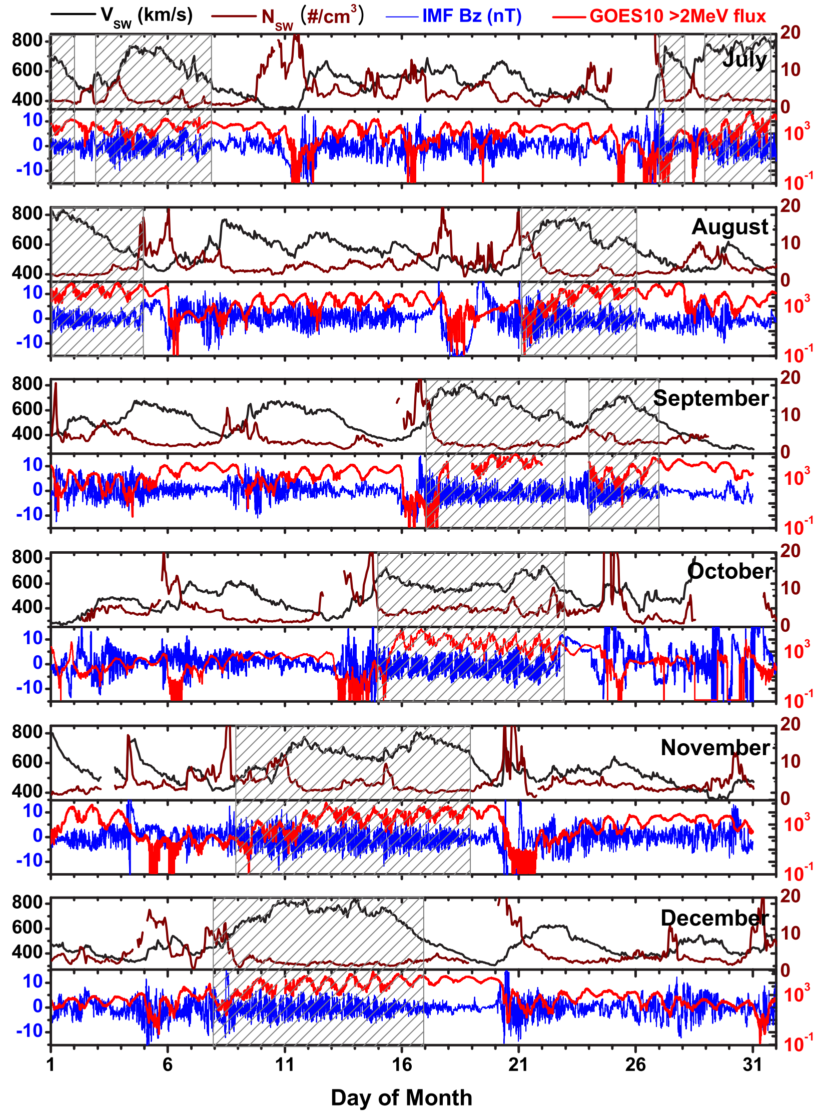

Figure 1. Solar wind speed Vsw (black line) and solar wind density Nsw (wine line) with 1-hour resolution, IMF Bz (blue line) with 4-min resolution as observed by ACE, and the geosynchronous >2 MeV electron flux as observed by GOES 10 (red line) with 5-min resolution for July through December 2003. Hatched gray box regions indicate the intervals that were studied in the present work.

(VELOX) [*Smith*, 1995] at Halley station, Antarctica (L = 4.3; MLT = UT − 3 hours). This station observes chorus emissions that are ducted to the ground and provides good coverage of the chorus emissions at L = 3–7 that interact with relativistic electrons [*Smith et al.*, 2004a, 2004b]. The data have been found to clearly show enhanced dawnside chorus activity after storms, peaking in intensity at ∼1000 MLT, consistent with what has been observed in space [*Smith et al.*, 2004a]. In our study we use both spectrogram plots and line plots of the mean log wave amplitudes averaged over the five lower channels between 0.5 and 3 kHz (see Figures 2 and 3 below). We have used this frequency range because lightening-generated spherics dominate frequencies above about 5 kHz, whereas the chorus waves of interest typically show as periods of enhanced wave amplitudes extending up to ∼2–3 kHz [*Smith et al.*, 2004a].

3. Case Studies

[10] Figure 2 shows the VELOX wave data (top two panels), low latitude ground H, and geosynchronous electron and proton flux data on 25 August 2003. The occurrence of substorm onset is identified based on the particle injection as observed by LANL spacecraft and the low-latitude H bay, as indicated by vertical dashed lines, and the onset times are given at the top of Figure 2. Although we only show particle flux data from a few selected LANL spacecrafts in Figure 2 and Figure 3, we have checked both electron and proton flux data from all available spacecrafts in order to determine the onset times. For most of the

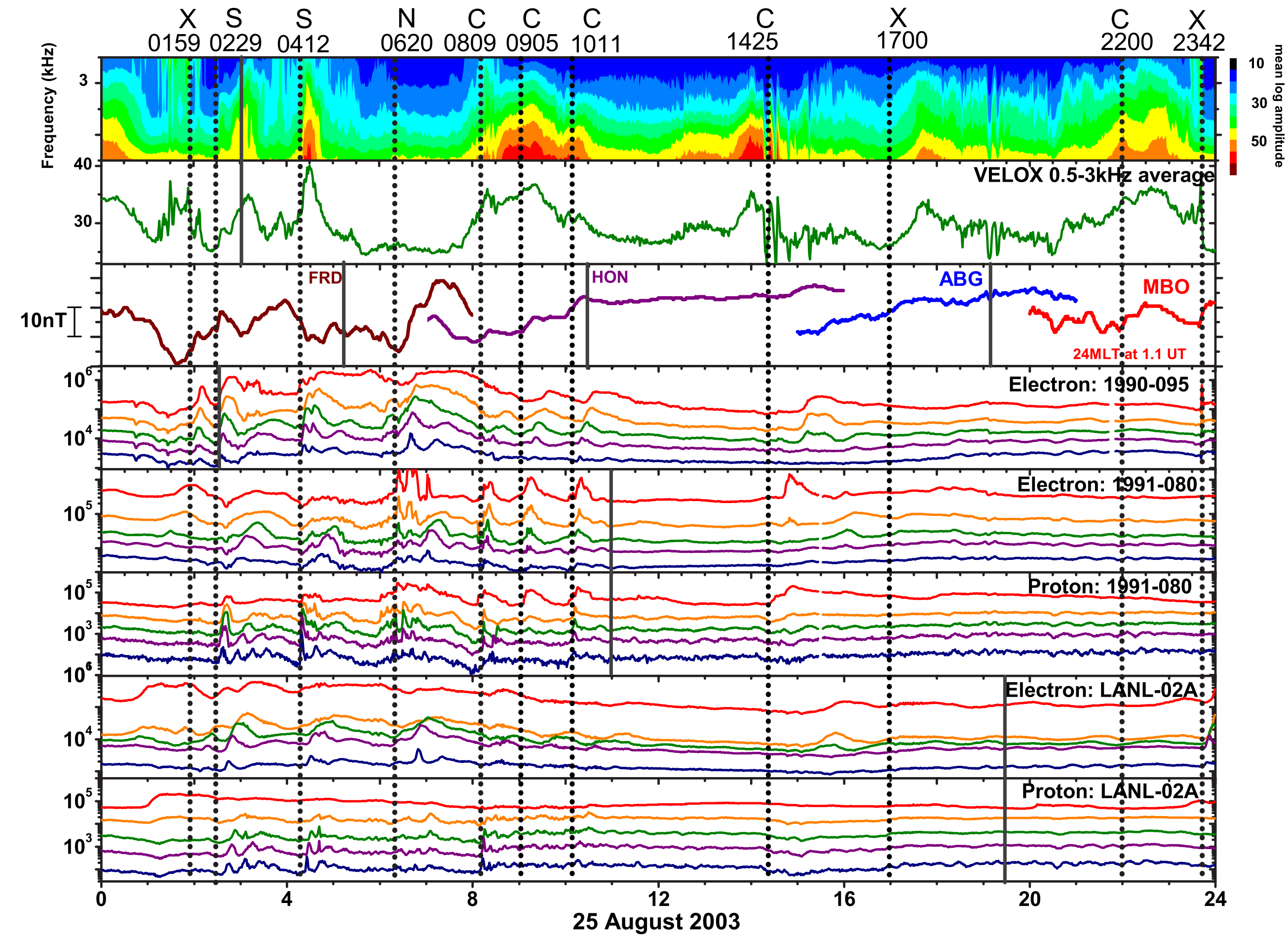

Figure 2. Spectrograms of the VLF/ELF Logger Experiment (VELOX) wave observations from Halley research station (L = 4.3, 0.5–3kHz) for 25 August 2003 (upper panel), the average of amplitudes of lower five channels, 0.5, 1, 1.5, 2, and 3 kHz of VELOX (second panel), ground midlatitude H observations from three stations selected so that the region near midnight is covered for each substorm (third panel), energetic electron fluxes from three selected LANL geosynchronous orbit spacecraft for lower five energy channels covering the energy range 50–315 keV (middle three panels) and proton fluxes from two LANL spacecrafts for 50–400 keV (bottom two panels). Vertical gray lines indicate the UT of magnetic midnight for the observations shown in individual panels. Vertical dashed black lines indicate substorm onsets.

substorms except for the 0620 UT event, there is a notable chorus enhancement around the onset time. We have classified the association of the substorms with the corresponding wave enhancements into four types as indicated by the letters at the top of the figure.

[11] First, for the 0229 and 0412 UT substorms, the wave intensity started to enhance right after the substorm onset, although the 0229 onset might have been followed by another onset at ~0300 UT. Note that for these two onset times, the Halley station was at ~23.5 and ~1.2 MLT, respectively. The injected electrons at the substorm expansion phase can be the cause of those chorus wave enhancements near midnight, which is consistent with the suggestion by *Smith et al.* [1999]. We classify this type of association between the substorm and wave activity as "S-type."

[12] In contrast, for the 0809 substorm, the chorus started to enhance prior to the substorm onset. At this time, the Halley station was in the dawn sector, and therefore, as suggested by *Lyons et al.* [2005], this is the chorus enhancement associated with the electrons that are convected from the tail to the near-Earth dawnside during the enhanced convection period of the substorm growth phase. As also suggested by *Lyons et al.* [2005], the enhanced wave intensity is expected to decline sometime after the convection reduction. The substorm onset time can approximately indicate the convection reduction time. Indeed, the enhanced waves declined somewhat after the 0809 onset. However, we notice that the decrease is not substantial, and the chorus amplitude increased again. This is due to the new growth phase prior to the new onset at 0905 UT. The enhanced wave then declined substantially after the new onset and even further decreased after another onset at 1011 UT. A similar type of association, with the waves enhancing sometime before onset and decreasing sometime after or around the substorm onset, is seen for the substorm

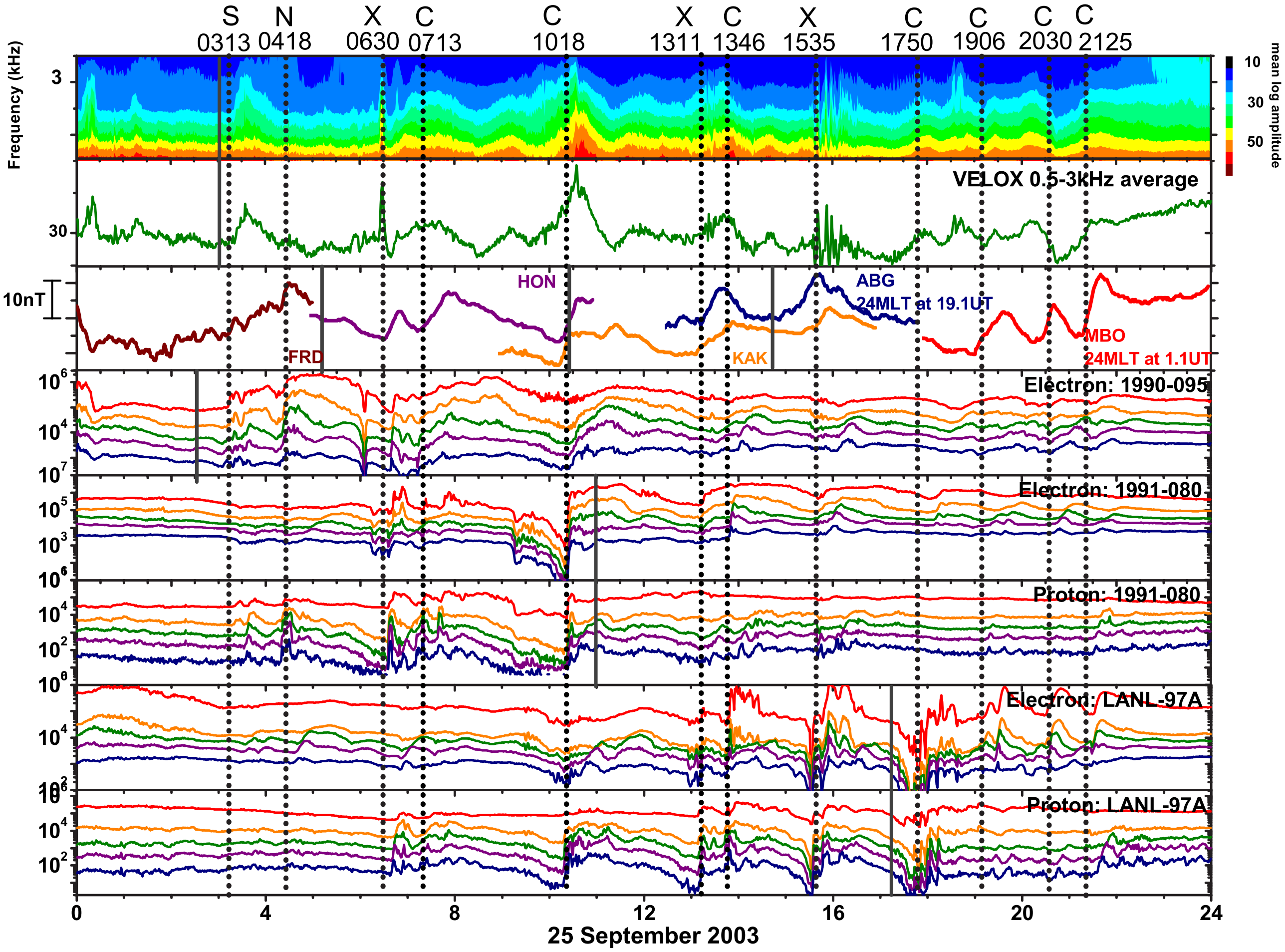

Figure 3. Same as Figure 2, except for 25 September 2003.

event at 1425 UT, the onset time of which was determined based on the proton flux data (not shown). Also the event at 2200 UT may be categorized as the same type although this event is less clear than the earlier ones. These are all distinguished from the S-type events above, and we refer to them as "C-type" association.

[13] More examples of S-type and C-type are shown for another interval in Figure 3. The 0313 substorm onset is shortly followed by a chorus wave enhancement near midnight, which therefore corresponds to the S-type association. Several C-type events are found when the Halley station was away from the midnight region: the events at 0713, 1018, 1346, 1750, 1906, and 2030 UT, and a somewhat less clear one at 2125 UT. Note that some of the C-type events are seen on the duskside, and these events could be associated with electrons convected in from the tail that have azimuthally drifted to the duskside.

[14] We note that there are cases where there is no obvious wave enhancement associated with either the substorm growth phase or the substorm expansion phase. Examples are events at 0620 UT in Figure 2 and 0418 UT in Figure 3. We refer to these cases as "N−type." Also, for some substorms, a wave enhancement exists around the onset times, but a specific type of association can not be determined. An example is the 0159 UT event in Figure 2, where the wave activity increased prior to the onset, abruptly decreased near the onset time, but then briefly increased. The fact that the wave intensified prior to the onset implies that this is not a S-type, but the later brief enhancement right after the onset may be related to the substorm injection considering that the station was near midnight. However, the fact that the wave activity extends well above 3 kHz up to 10 kHz (data above 3 kHz not shown) leads us to not classify this event as chorus but seems to suggest that this is possibly auroral hiss. The wave event at ∼2342 UT may also be auroral hiss. (See more discussion in section 5).

[15] It is difficult to categorize the association without ambiguity for those events. Also near 1700 UT, the ground H increase at ABG in the premidnight sector and the proton flux data at LANL-97a and 1994-084 near midnight (not shown) indicate some weak flux enhancements, implying a possible substorm onset. The chorus enhancement is clear sometime after the onset, implying that this is clearly not a C-type event. However, the wave enhancement time is rather too far from the onset time, and considering that the Halley station was at 1400 MLT, it may not be appropriate to classify this event as a S-type event either. For the statistical work in the next section, we have imposed more specific quantitative criteria to define each type of association. Under this classification scheme, the above event is classified as X-type. Other examples of X-type

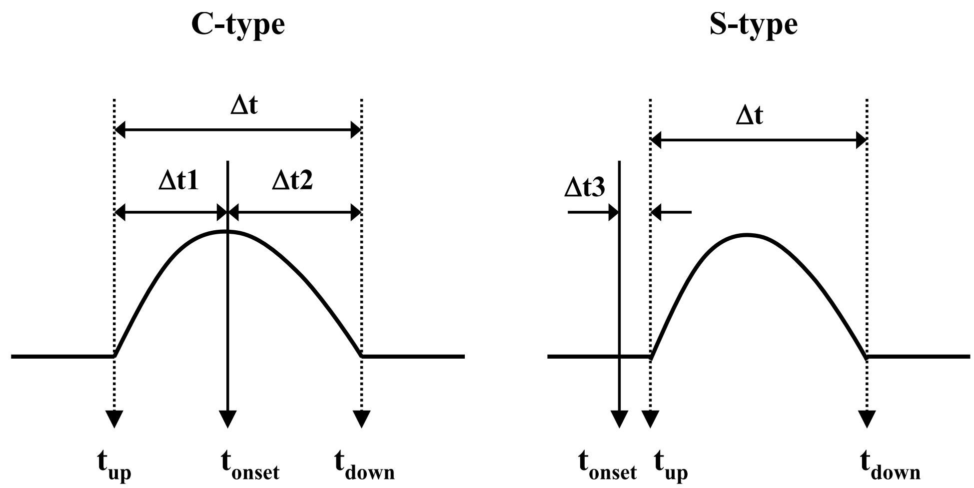

Figure 4. (left) Schematic illustration of the C-type: t_{up} means wave increase time, t_{down} the wave decrease time, and t_{onset} the substorm onset time. Δt1 indicates the wave duration prior to the substorm onset, Δt2 indicates the wave duration after the onset, and Δt is the total duration of the wave enhancement. (right) A similar illustration for the case of S-type. Δt3 indicates the wave start time relative to the substorm onset.

associations seen in Figure 3 are the event at 0630 UT where a very short-lasting sharp wave enhancement slightly precedes the onset, the event at 1311 UT where the wave enhancement occurs after this onset but can not be distinguished from the possible enhancement during the growth phase of the later onset at 1346 UT, and the event at 1535 UT where the wave amplitude fluctuates rather irregularly. For X-type events, the wave enhancement may not be related to the substorm activity, or may be related but the specific relation could simply not be determined.

4. Statistical Results

[16] On the basis of the examples above and those in the work of *Lyons et al.* [2005], we categorize the associations between substorms and chorus activities into the four types described above. For the statistical analysis, we define the four types of associations more specifically. First, we define "C-type" to be the case where the chorus starts to intensify 10 min or earlier prior to the substorm onset and then declines to approximately the previous value within 60 min after the substorm onset (see Figure 4 for a schematic illustration). This is the type where the wave excitation is associated with the electrons transported by the enhanced convection during the substorm growth phase. We define "S-type" to be the case where the wave enhancement begins within 10 min after the substorm onset (see Figure 4 for a schematic illustration). This is the type where the chorus excitation is due to the injected electrons at the time of the substorm onset. For "X-type" cases, we require that a wave activity exists around the substorm onset time (within 10 min) but a specific type of association cannot be determined. This X-type includes some limited number of events in the premidnight region that are likely auroral hiss. We define "N-type" to be the case where there is no significant wave enhancement within the 10 min around the substorm onset. In order to identify quantitatively a chorus enhancement event, we have used the criterion that the average amplitude over the lower five channels, i.e., 0.5, 1, 1.5, 2, and 3 kHz, increases by ≥2 dB which corresponds to an increase of ≥50% in the power spectral density relative to 10^{-33} T^2/Hz.

[17] On the basis of the particle injection and the low-latitude and midlatitude H bay, we have identified a total of 657 substorm events. This was done for 83 days of the high-speed stream intervals where the solar wind speed was ≥500 km/s and the >2 MeV geosynchronous electron flux was substantial. These times are indicated by hatched gray boxes in Figure 1. For each substorm event, we have checked whether or not there was a wave enhancement event based on the criterion described above and determined the type of the association according to the categorization above.

[18] The magnetic local time (MLT) distribution of the Halley station observations for those 657 events is shown in the Figure 5. The largest number of events selected was at 1200–1400 MLT and the smallest at 0400–0600 MLT. In Figure 5, the four types of associations are distinguished. About 45% of the substorm events (296 events out of 657) exhibit the C type association with the wave enhancement, and ~17 % (115 events out of 657) show the S-type association. The other events show either X-type association (~16%) or N-type (~22%). Most importantly, the occurrence percentage of the C-type events is largest in the dawn to postnoon regions: ~66 % of the events at 0400–1400 MLT show the C-type association. The C-type events are still seen at late afternoon and later, but the occurrence percentage substantially decreases for those later MLT sectors. In contrast, the occurrence percentage of the S-type events is dominant near midnight: ~59% of the events at 2200–0200 MLT show the S-type association. It is substantially lower at other MLTs, in particular, for 0400–2000 MLT. These are consistent with what is discussed above and with the suggestion by *Smith et al.* [1999]. On

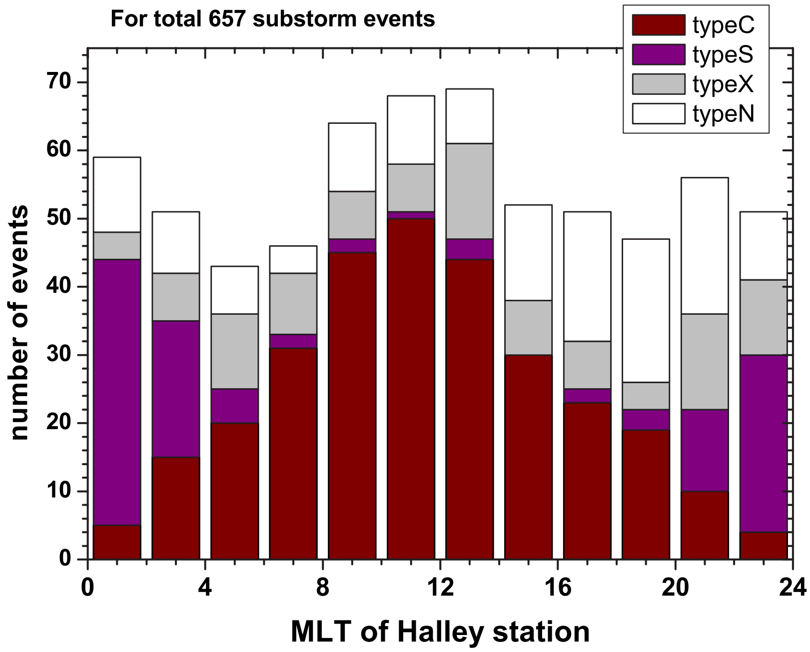

Figure 5. MLT distribution of Halley station association types for the 657 substorm events identified during the high-speed solar wind stream intervals.

the other hand, the occurrence percentage of N-type is more significant in the afternoon through premidnight region, namely, at 1400–2200 MLT regions than in the other MLT regions. Since this is the type where there was no wave excitation before or after the substorm occurrence, it may imply, in a statistical sense, that the chorus excitation by either convected electrons or substorm-injected electrons is less effective in the late afternoon-to-premidnight regions than in the other MLT regions, which could be the result of some wave-driven precipitation at earlier MLTs limiting access to this local time region. There is no noticeable tendency for the MLT distribution of the X-type as they were found at all MLTs without an obvious preference. Table 1 gives a simple summary of the statistical results.

[19] Figure 6 shows statistical summaries of the wave enhancement duration and the time relative to the substorm onset when the enhanced wave amplitude drops (t_{down} in left plot of Figure 4) for the C-type events. For these statistics, we have used 121 and 202 events, respectively. This is because for some events the quantitative analysis is not practical as the wave increase and/or decrease times could not be determined precisely although the association with the onset is clear based on a visual inspection. The 121 events are the events where both the wave increase and decrease times are well-defined, and the 202 events are those where at least the wave decrease time is clearly defined. The results show that on average, the enhanced chorus lasts for ~51 min (total duration time) and drops to approximately the previous value ~16 min after the substorm onset (wave drop time relative to onsets). This means that the wave starts to increase ~35 min on the average prior to the substorm onset. It is interesting and reasonable that this ~35 min is similar to the typical substorm growth phase duration.

Table 1. A Statistical Summary of the Association Types

Types	Number of Events, %	Main Features		
C	296 (45)	includes ~66% of the events at 0400–1400 MLT	Wave duration ~51 min[a]	Wave drop ~16 min after onset[b]
S	115 (17)	includes ~59% of the events at 2200–0200 MLT	Wave duration ~32 min[c]	Wave increase ~6 min before onset[d]
X	103 (16)	no noticeable feature on MLT distribution		
N	143 (22)	more events at 1400–2200 MLT than in the other MLTs		
Total	657 (100)			

[a]Averages were obtained using 121 events.
[b]Averages were obtained using 202 events.
[c]Averages were obtained using 89 events.
[d]Averages were obtained using 113 events.

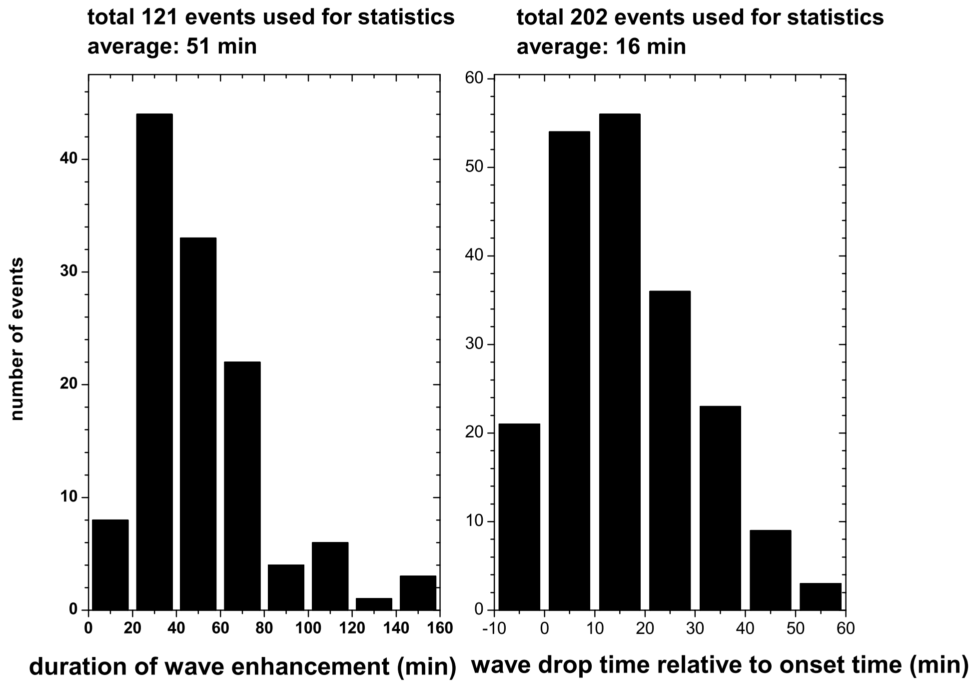

Figure 6. Total duration of wave enhancements (Δt in Figure 4) and wave amplitude drop time relative to substorm onset time for the C-type events (Δt2 in Figure 4).

[20] Similar summaries for S-type events are shown in Figure 7 where the limited number of events is used because of the reasons mentioned above. The chorus starts to enhance ~6 min (average over 113 events) after the substorm onset and lasts for ~32 min (average over 89 events) before it drops substantially. Note that the average duration of the enhanced waves, 32 min, for these S-type events is ~63% of that of the C-type case, 51 min, implying that the enhanced chorus waves caused by the convected electrons

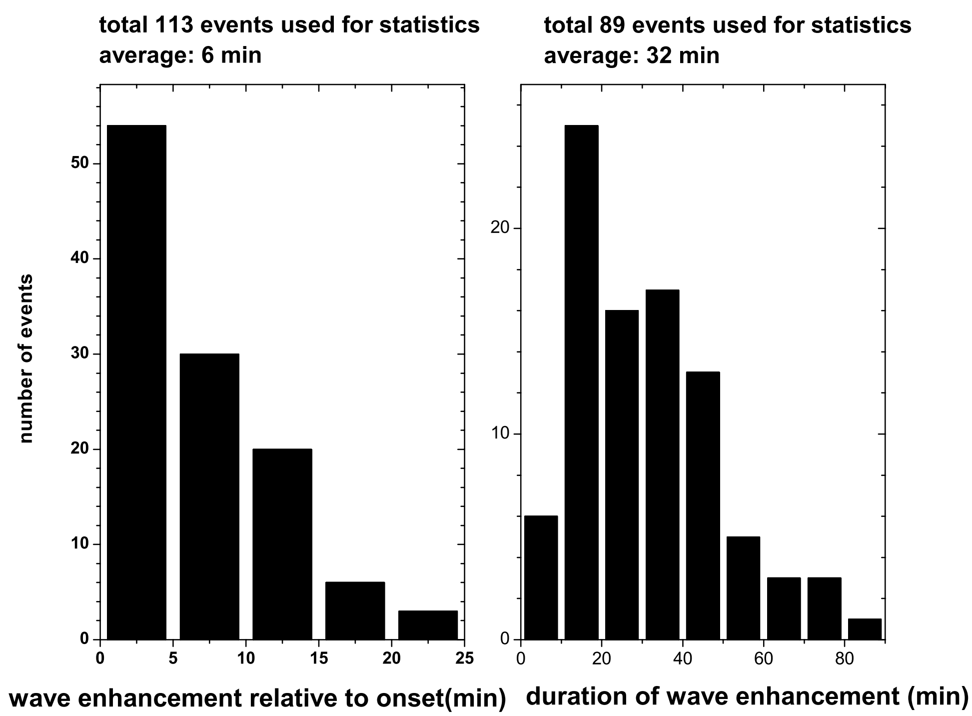

Figure 7. Wave enhancement start time relative to the substorm onset (Δt3 in Figure 4) and duration of wave enhancements for the S-type events (Δt in Figure 4).

last longer than those caused by the substorm-injected electrons.

5. Summary and Conclusions

[21] In this paper, we have performed a statistical analysis on the association between substorms and chorus activity using 657 substorm events and the VELOX wave data from Halley station during the high-speed stream intervals in July through December 2003. The main goal of this work is to test the statistical significance of the idea proposed by *Lyons et al.* [2005] that it is the periods of enhanced convection that precede substorm expansions and not the expansions themselves that lead to the enhanced dawnside chorus wave intensity that has been postulated to cause the energization of relativistic electrons. The idea implies that the dawnside chorus should enhance during the substorm growth phase and decline after or around the substorm onset, which we refer to as C-type association in the present work. This is distinguished from the near-midnight chorus intensification that we refer to as S-type association, which occurs after the substorm onset and is therefore directly associated with the substorm-injected electrons. Our statistical study based on the 657 substorms indicates other cases as well where there is either no clear association between substorms and enhanced wave activity or where there is no wave enhancement around the onset time. Specifically, we have obtained the following statistical results.

[22] 1. Out of total 657 substorm onsets, 45% show C-type association with the chorus enhancement, and 17% are S-type association events. For 16% of the substorm events, a wave enhancement exists around the onset time, but a specific type of the association could not be determined, and the remaining 22% of the substorms are associated with no notable wave enhancement.

[23] 2. For the C-type events, the occurrence percentage is most significant at dawn to postnoon local times: ~66 % of the events at 0400–1400 MLT show the C-type association. In contrast, the S-type events are dominantly found near midnight: ~59% of the events at 2200–0200 MLT show the S-type association, which is in line with the result of *Smith et al.* [1999] that postmidnight ELF/VLF wave events are a signature of the substorm expansion phase which was named as "substorm chorus events (SCEs)."

[24] 3. For the C-type waves, the chorus starts to enhance ~35 min prior to the substorm onset and drops ~16 min after the onset on the average. For the S-type waves, it starts to increase ~6 min after the onset and remains enhanced for ~32 min on the average. This means that the enhanced chorus waves caused by the convected electrons in the dawn to postnoon region last longer than those caused by the substorm-injected electrons near midnight.

[25] Therefore we conclude that a large number of chorus enhancements at dawn to postnoon local times that can lead to relativistic electron acceleration are associated with enhanced convection periods of the substorm growth phase (C-type waves), although there are cases where this association does not hold or can not be determined. This statistically supports the idea proposed by *Lyons et al.* [2005] to a large extent. This is distinguished from the chorus enhancement near midnight that is caused by substorm-injected electrons after onsets (S-type waves). Also note that Figure 5 indicates that a larger fraction of events are N-type cases at 1400–2200 MLT than at other MLTs, implying that the wave excitation either by enhanced convection or by direct onset injections is less effective in the afternoon to premidnight regions.

[26] The present results are limited by some ambiguities that our statistical method could not fully eliminate. First, our method was based on a rather simple requirement on frequency range and wave amplitude for identifying chorus events. Some wave activities above 3 kHz extending up to ~10 kHz in our study were regarded as hiss and absorbed into the X-type events. This might have affected our statistical results to some extent. Future work is needed to more clearly distinguish between chorus and hiss [*Smith*, 1995]. Identification of the plasmapause and the location of the Halley station relative to it would be crucial for such a study. Another source of ambiguities could be magnetosonic emission associated with the dayside cusp [*Newell and Meng*, 1988; *Russell et al.*, 2000]. Many events in our study were identified near the noon sectors, and the dayside cusp waves might be included in these events, which suggest an additional study in the future.

[27] As in the work of *Lyons et al.* [2005], we have used the substorm onset as an indicator of enhanced convection before the onset time and a reduction in convection after that time. As suggested by *Lyons et al.* [2005], it will be useful for a future work if the convection change can be determined by a more direct measurement of convection, such as SuperDARN radar measurements, than what we have used here.

[28] An interesting future work is a similar test of possible associations of chorus enhancements with continuous substorms or sawtooth-type injections during storm times that are not associated with corotating high-speed streams but associated with coronal mass ejections (CME). Some of those CME-driven storms have been shown to be accompanied by relativistic electron flux enhancements. If enhanced convection is indeed the principal cause of dawnside chorus, similar correlation should be expected with the continuous substorms or sawtooth events during CME-driven storms, although the situation may be complicated by the storm time disturbances that could affect the wave propagation down to the ground [*Smith et al.*, 2004a].

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