# Occurrence Patterns of Magnetospheric EMIC Waves During Geomagnetic Storms: Ground-based Observations at Auroral and Subauroral Latitudes

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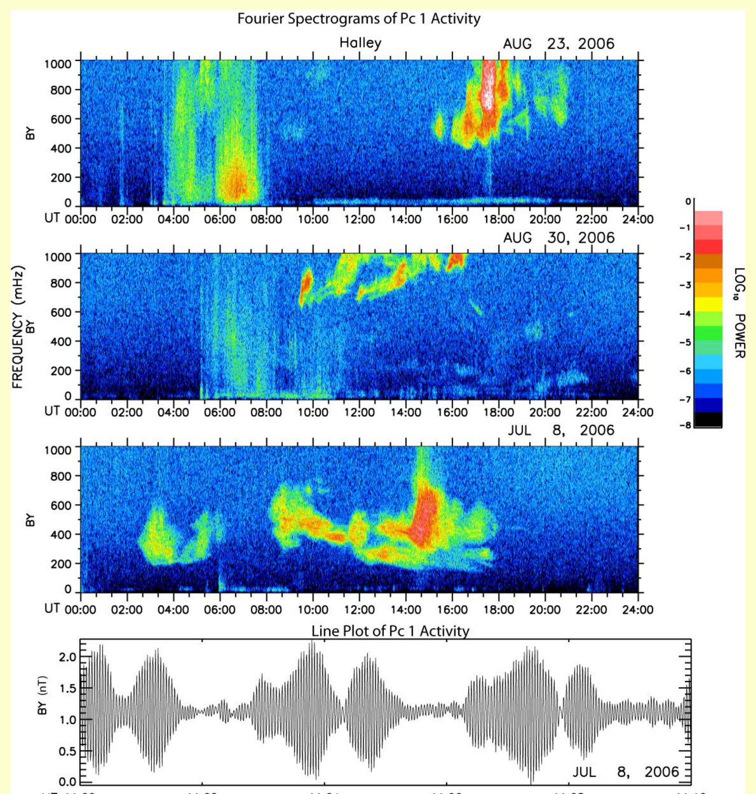
## Introduction

An increased occurrence of electromagnetic ion cyclotron (EMIC) waves in Earth's magnetosphere has long been noted during the aftermath of magnetic storms.

Such waves, classified as Pc 1-2 waves (0.1-5.0 Hz), have been suggested in many theoretical and some observational studies as a significant loss mechanism for both ring current ions and, via parasitic interactions, radiation belt electrons.

Such waves are observed routinely in space, and also by ground-based search coil magnetometers.




Although there have been many individual reports of EMIC wave activity, there are few comprehensive studies of their occurrence as a function of latitude, solar cycle, and/or storm phase.

Two recent exceptions are the studies of Bortnik et al. [JGR 2008], which surveyed EMIC waves during magnetic storm intervals from 1999 through 2006 at Parkfield, CA (*L* = 1.77), and Engebretson et al. [JGR 2008], which surveyed waves during 13 storm intervals in 2005 at Halley, Antarctica (*L* = 4.62).

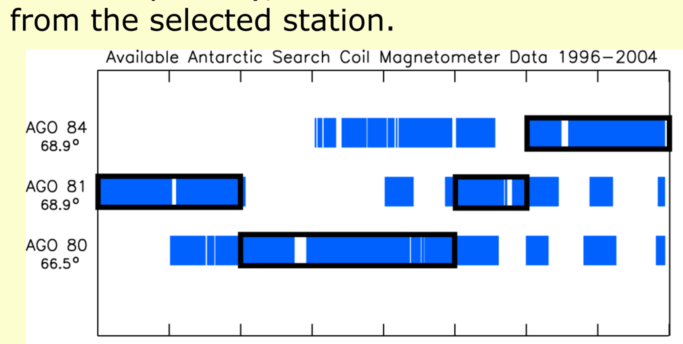
In this study we have applied the automated wave analysis technique described by Bortnik et al. [JGR 2007] to a large multi-year suite of data from search coil magnetometers deployed in automated geophysical observatories (AGOs) by the British Antarctic Survey at auroral latitudes in Antarctica. These instruments recorded 2 samples/s, so wave measurements are limited to a maximum of 1 Hz.

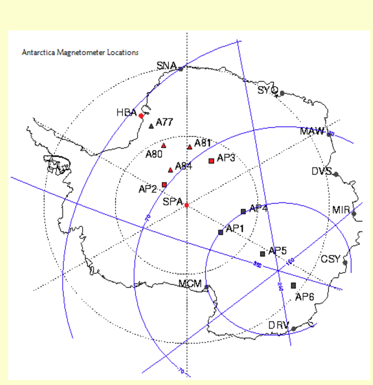
## Data Set

The table below shows the geographic coordinates of the BAS AGOs (left) and their magnetic coordinates (right) for epochs 1996 and 2003, calculated using the modelweb facility at NASA /GSFC, http://modelweb.gsfc.nasa.gov/models/cgm/cgm.html.

| Station | G LAT | G LON | M LAT | M LON | Noon MLT | L | Epoch |
|---|---|---|---|---|---|---|---|
| A80 | 80.7 S | 20.4 W | 66.3 S | 29.1 E | 14:46 | 6.28 | |
| A81 | 81.5 S | 3.0 E | 68.7 S | 36.0 E | 14:18 | 7.68 | 1996 |
| A84 | 84.4 S | 23.9 W | 69.2 S | 25.1 E | 15:05 | 8.07 | |
| | | | | | | | |
| A80 | | | 66.4 S | 29.3 E | 14:46 | 6.35 | |
| A81 | | | 68.8 S | 36.2 E | 14:19 | 7.76 | 2003 |
| A84 | | | 69.3 S | 25.2 E | 15:05 | 8.16 | |

The diagram below shows the availability of search coil magnetometer data from the three BAS AGOs from 1996 through 2003. The black boxes indicate the stations used during each year for this study. When possible (for example in January 1997), data from another station were used to fill in data missing from the selected station.



## Event Statistics

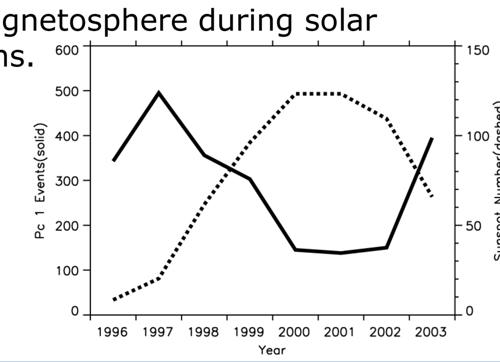
During the years 1996-2003, data were available for 2648 of the possible 2922 days, for a 90.6% coverage ratio. Of the 274 missing days, data from other AGOs were used for 78, or 28.5% of these, bringing the modified coverage ratio to 93.3%.

Each 2-hour UT interval was examined for the presence of narrowband Pc 1 wave activity between 0.2 Hz and 1.0 Hz with amplitude >=$10^{-4}$ $nT^2$-$Hz^3$ (in the yellow and red color ranges in the above spectrograms).

Wave events identified by the automated algorithm were verified by visual inspection of daily 0-1 Hz spectrograms. This led to removal of 94 "false positive" broadband noise events, and the addition of 857 "false negative" Pc 1 events that were not identified by the automated algorithm, leading to a total of 2325 events. Activity was highly variable, ranging from 72 "events" in November 1997 to 1 "event" in April 2000.

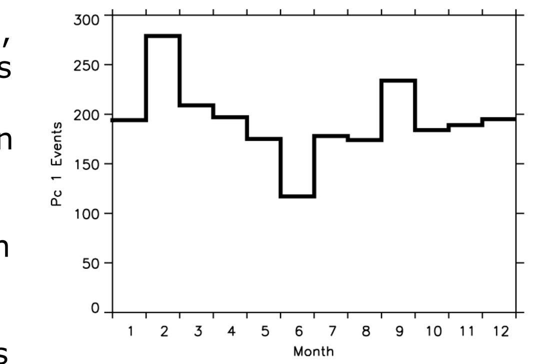
## Dependence on Solar Cycle

A minimum in occurrence is evident during 2000-2002, corresponding to solar maximum. The anticorrelation between Pc 1 occurrence and sunspot activity is well known [e.g., the review by Kangas et al., 1998], and is often attributed to an increase in $O^+$ levels in the magnetosphere during solar maximum conditions.



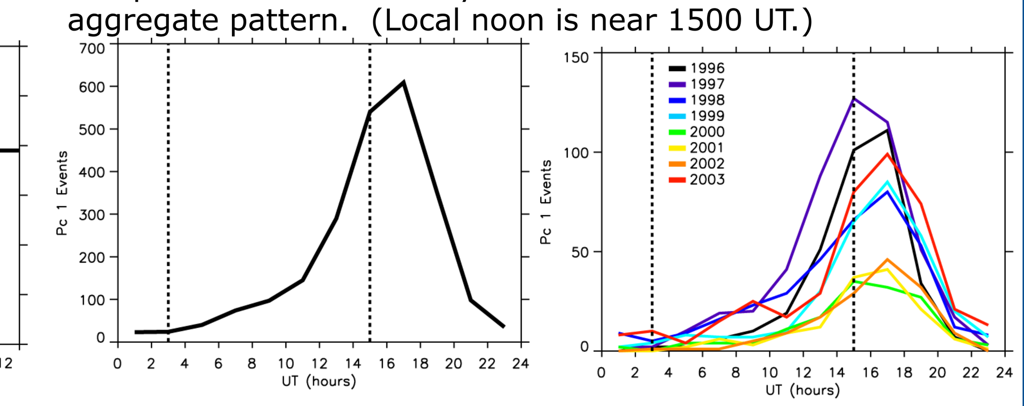

## Dependence on Season

No significant seasonal variation is evident in this data set, but the absence of data during one year from Jan., Jul., and Nov., and during two years from Oct. and Dec. suggests that the true seasonal variation may have a modest winter minimum, consistent with reduced horizontal propagation (by means of ducting) during Antarctic winter, and roughly symmetric occurrence patterns during fall and spring.



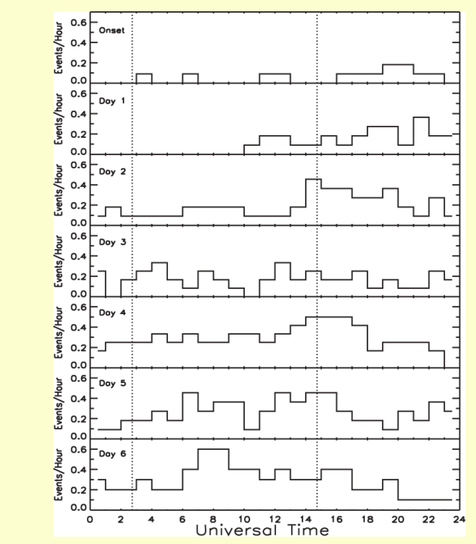

## Dependence on Local Time

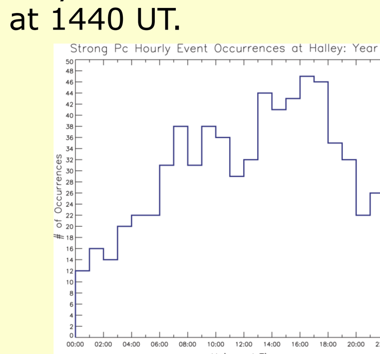
The local time dependence for all 8 years is shown on the left. The pattern for individual years shows little deviation from the aggregate pattern. (Local noon is near 1500 UT.)




## Comparison to Halley (L = 4.62)

Engebretson et al. [2008a] found a much more isotropic distribution of Pc 1 events as a function of MLT at Halley, Antarctica. Left: post-storm. Below: all days in 2005. Local noon at Halley is at 1440 UT.




## Dependence on Storm Phase

In this section we present superposed epoch plots of Pc 1 event occurrence for several categories of geomagnetic storms, for high speed streams, and for storm sudden commencements (SSCs). Each plot shows a color-coded grid of fractional occurrence (0.5 = 50%) as a function of Universal Time (in 2-hour bins) during a 16-day interval, from 6 days before to 10 days after the designated date. As above, local noon is near 1500 UT.

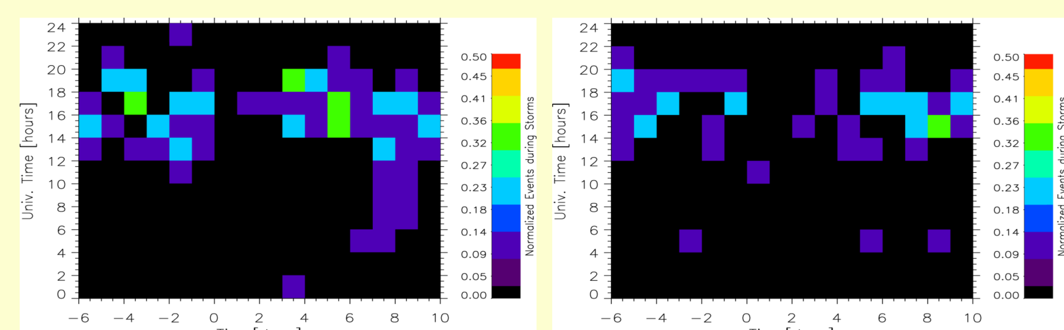
For most of the following plots, the zero epoch is the day of minimum $D_{st}$, or of SSC occurrence. For high speed streams it is the onset of convection. The McPherron storm list includes both the start and end of main phase.

We begin with the lists of moderate and intense storms identified by Bortnik et al. [2008]. These were selected to be "clean," isolated storms without multiple onsets. Bortnik et al. [2008] identified 12 storms in each category between 1999 and 2005. Our data base included 9 storms in each category, between 1999 and 2003.

### Isolated Storms

(Bortnik et al. [2008])

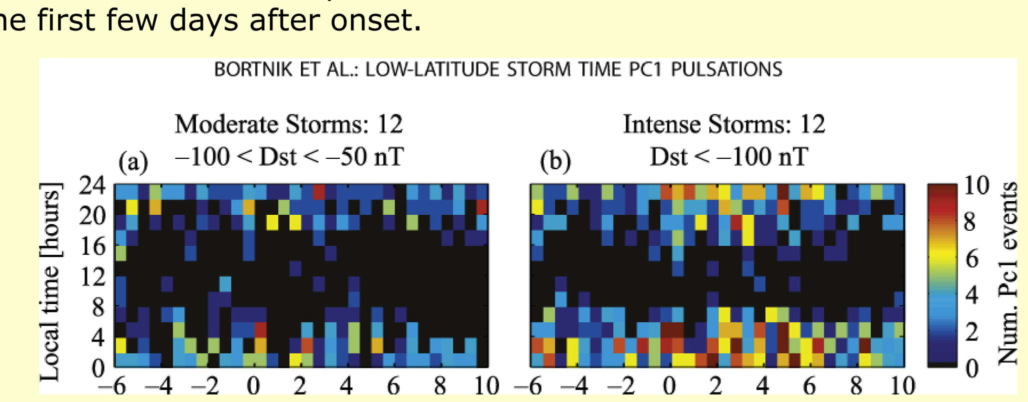
Moderate Storms (9) -100 ≤ min $D_{st}$ < -50 nT | Intense Storms (9) -450 ≤ min $D_{st}$ < -100 nT




The salient features of both distributions include near-noon or shortly post-noon occurrence maxima, a drop during and shortly after the day of minimum $D_{st}$, and roughly similar occurrence frequencies before storm onset and during the late recovery phase.

Because these storms were selected to be isolated, the pre-storm period does not include recovery phase intervals of prior storms. Events in later categories shown do include such intervals, however.

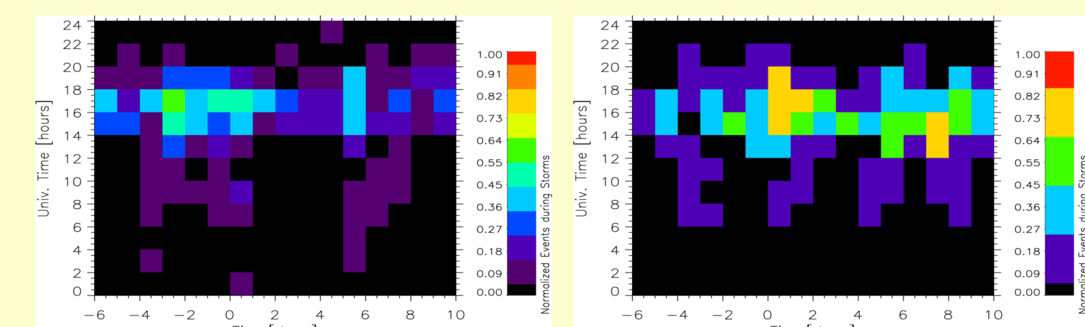
The distributions found by Bortnik et al. [2008] at L = 1.77 are shown below. Evident is a deep dayside minimum and a maximum from dusk to dawn that varies little with storm phase. Occurrence increases at all local times during the first few days after onset.




### High Speed Streams

(Denton and Borovsky [2008])

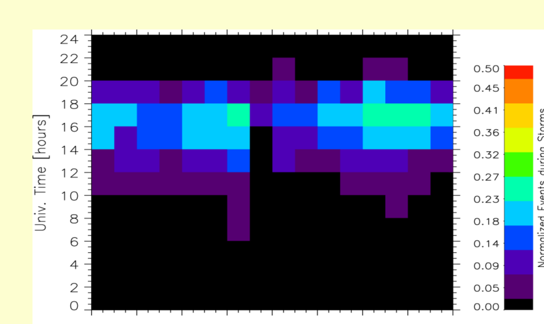
Noisy before Convection Onset (20) (note the 0-1 color scale) | Calm before Convection Onset (5) (note the 0-1 color scale)




These events, during 1996 and 2003 only, do not necessarily lead to magnetic storms. Both sets are characterized by high wave occurrence probabilities, again mostly near noon, but with greatly increased occurrence during the first 2-3 days of magnetospheric activity, especially during intervals following calm periods.

### Storm Sudden Commencements

**(186 events on the NOAA list, 1996-2003)**

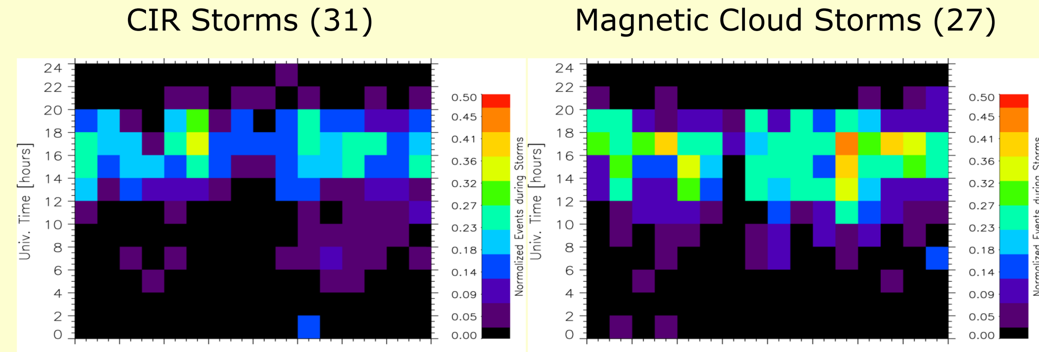



As expected, Pc 1 activity is enhanced on the day of SSC occurrence. Again, SSCs do not necessarily lead to magnetic storms. However, the decreased Pc 1 occurrence on days 1-3 and increases on days 4-9 are consistent with most SSCs being associated with storms.

### Varieties of Magnetic Storm Drivers

Yermolaev [2007]

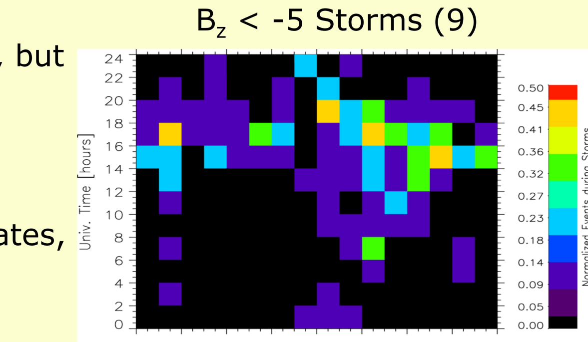
CIR Storms (31) | Magnetic Cloud Storms (27)




Considerable Pc 1 activity precedes CIR and MC storms, but is not as prominent before storms produced by strongly southward IMF Bz.

Dayside activity again dominates, but with different occurrence rates during main and early recovery phases in each category.

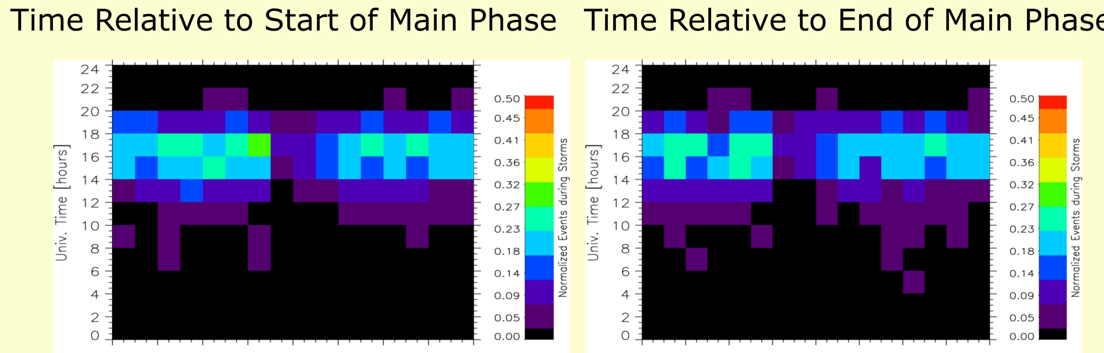
$B_z$ < -5 Storms (9)




### Occurrence During Initial Phases

**(123 storms on the "McPherron list," 1996-2003)**

Time Relative to Start of Main Phase | Time Relative to End of Main Phase




Comparison of these plots shows that waves occur rather frequently after storm onset, and much less frequently after the end of the main phase. Occurrence frequency during the recovery phase is slightly lower than that pre-storm.

The low occurrence rates shown here are due in part to the inclusion of data from 2000-2002. When storms during these years are removed, the occurrence rates increase, but there is no significant change in temporal or local time patterns.

## Summary of Observations

1. Pc 1 waves are observed on the ground at auroral latitudes at least as often prior to magnetic storms as during storm recovery. They exhibit a clear minimum during the early recovery phase.

2. Pc 1 waves observed at ground stations at auroral zone latitudes occur predominantly on the day side, peaking shortly after local noon. This diurnal pattern is fully consistent with the AMPTE CCE observations of Anderson et al. [1992] in the equatorial outer magnetosphere (L > 6). In addition, there is only a small difference in MLT patterns pre-storm and post-storm.

This local time pattern is in contrast to that at subauroral latitudes (e.g., Halley) where the distribution is more isotropic and shows an afternoon peak in the first two days of the recovery period, and especially differs from that at low latitudes (e.g. Parkside), where Pc 1 waves occurred predominantly between dusk and dawn during all storm phases. The Anderson et al. [1992] diurnal patterns for L < 6 are consistent with these ground-based results.

3. Our observations of increased wave activity during the initial stages of convection during high speed streams are consistent with the observations by Denton and Borovsky [2008] of increased density of plume material convecting to the dayside magnetopause at these times. They noted roughly double the density during high speed streams which followed very calm periods as compared to streams following periods when higher levels of convection persisted, and we observed at least a 50% increase in Pc 1 occurrence during the former, compared to the latter.

## Interpretation

The outer dayside magnetosphere is known to often be marginally unstable to ion cyclotron instabilities, which can be triggered by solar wind compressions [e.g., Anderson and Hamilton, 1993]. It is thus not surprising that there is a diurnal maximum of Pc 1 occurrence at high L values near local noon. The addition of denser plasmaspheric plume material to the outer magnetosphere is also expected to increase the growth rate of Pc 1 waves.

## Future Work

There has been some controversy whether Pc 1 events occur often during main phase, and whether if they do, they might not appear in ground records [see, e.g., Engebretson et al., 2008a, b]. The data presented here suggests that Pc 1 events do occur during the main phase of some storms, and storms with different drivers have different patterns. However, the time resolution (1 day) used in this presentation is inadequate to fully characterize this. Studies of example events (not shown) suggest that solar wind pressure increases are responsible for at least some of these events, which again occur predominantly on the day side. Further analysis using this data set will be required to adequately focus on the Pc 1 activity observed during main and early recovery phases. This analysis will also include a more detailed look at the correlation between wave occurrence and dayside plumes.

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