

In Situ and Ground-based Observations of Pc1 Pearl Pulsations



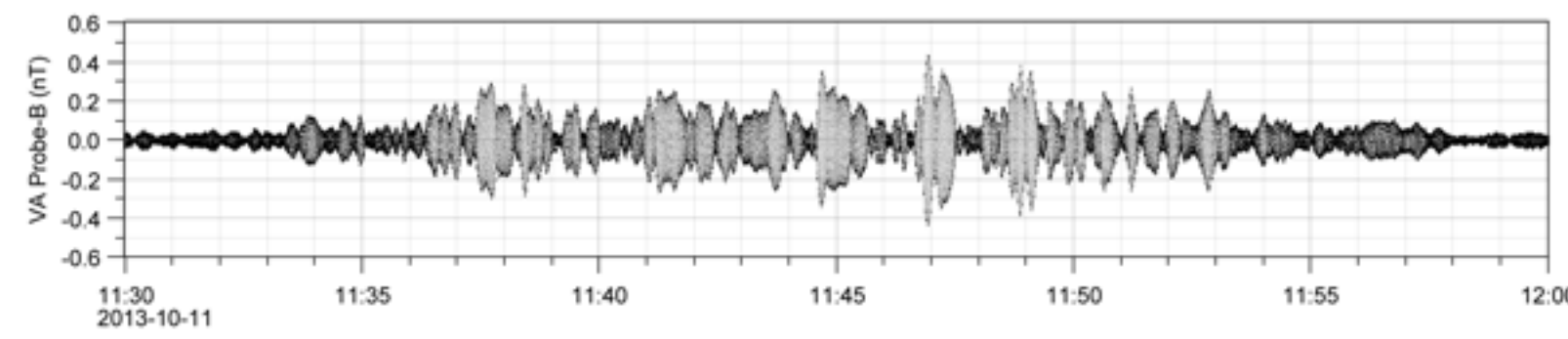
K. W. Paulson¹, C. W. Smith¹, M. R. Lessard¹, J. C. Zhang¹, M. J. Engebretson², R. B. Torbert¹, C. A. Kletzing³

¹University of New Hampshire, Durham, NH • ²Augsburg College, Minneapolis, MN • ³University of Iowa, Iowa City, IA

Abstract

Pc1 pearl pulsations have been observed by ground-based magnetometers since the mid-1930s, and have since been identified as a class of electromagnetic ion-cyclotron waves. While they make up a significant fraction of total observed Pc1 wave activity, there exist few direct observations by orbiting satellites. We present here simultaneous observations of Pc1 pearl waves by the Van Allen (VA) Probes spacecraft as well as observation stations on the island of Svalbard and Halley, Antarctica, with which the spacecraft were in close conjunction. The short time durations in the VA Probes data compared to the ground station observations suggests a narrow spatial extent of the source region. We discuss merits of current competing generation mechanisms in light of this new observation.

What are Pc1 Pearl Pulsations?



Pc1 pearl pulsations are electromagnetic plasma waves on the order of ~ 0.2 -5 Hz [Sucksdorff (1936)]. They are made up of discrete wave packets forming a string-of-pearls waveform configuration (see above), which appear as near-vertical stripes of wave power in a frequency-time plot. These wave packets are regularly spaced in time on the order of 10s to 100s of seconds, implying a generation mechanism that is periodic in nature. They may exhibit rising or falling tones, and the frequency sweep of each element is constrained to some fractions of a Hz.

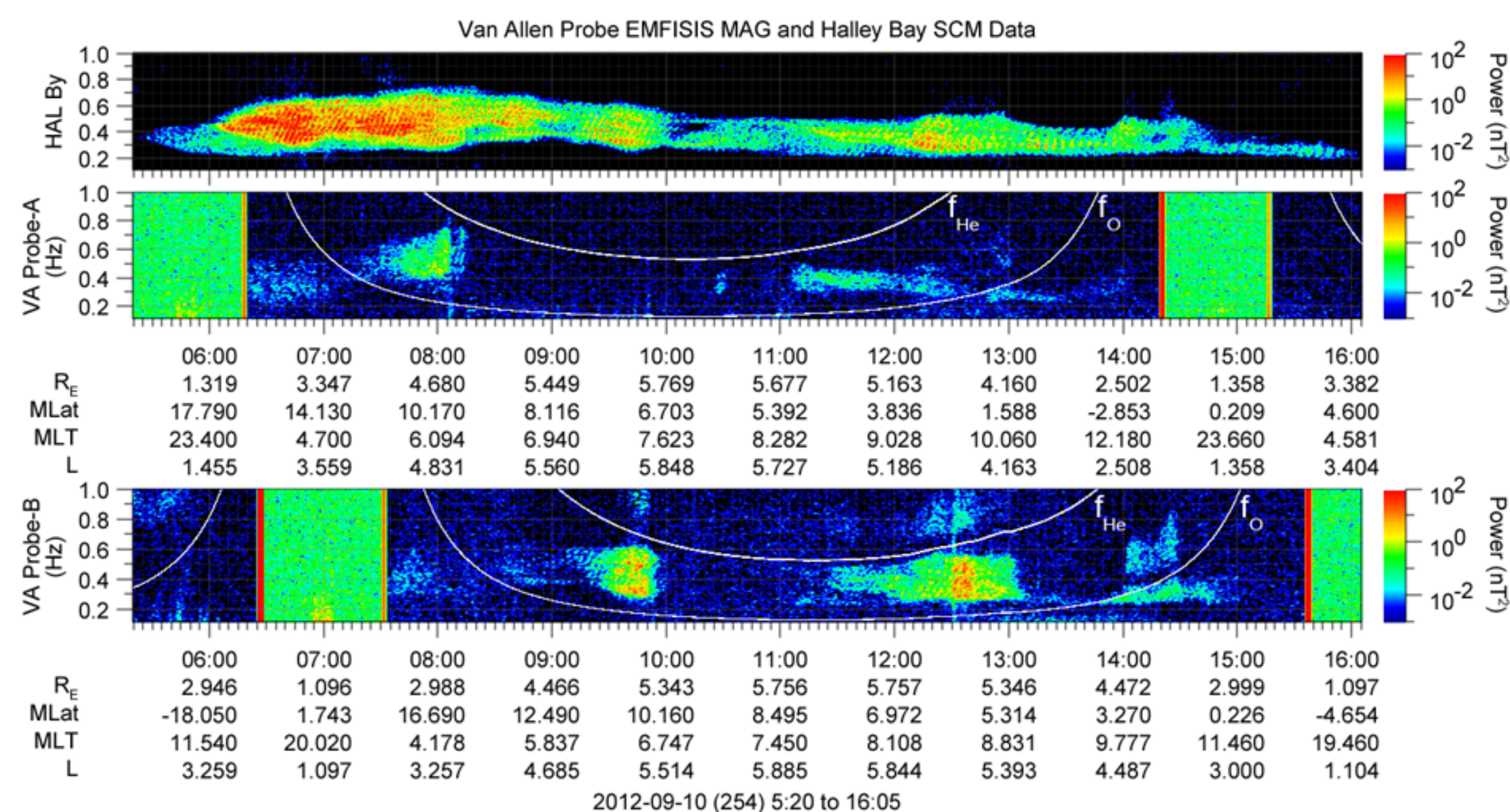
Pearls are widely accepted as a subset of electromagnetic ion-cyclotron (EMIC) waves [Cornwall (1965)], which are left-hand polarized field-aligned wavemodes. Though commonly seen at ground-based stations, they are rarely observed in space, so the local conditions leading to their generation is not well understood. Ground observations suggest they are most often seen at lower geomagnetic latitudes and in the morning sector.

Mechanism of Generation

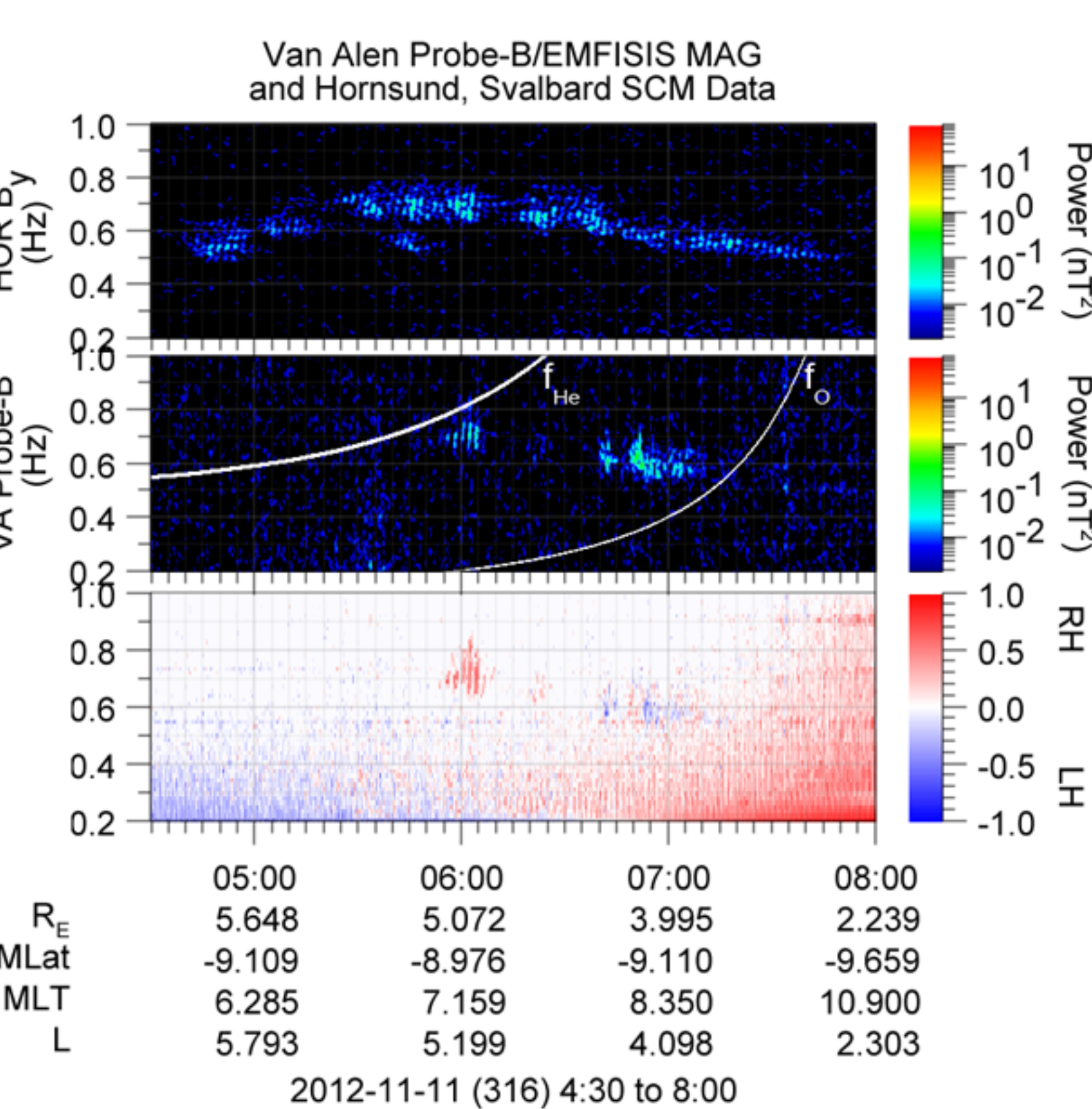
Previously, these waves were thought to be generated as wave packets reflecting between ionospheric layers (Bouncing Wave Packet, or BWP, theory). As wave elements passed through the equatorial region, they would be reenergized and so replenish any wave power lost at the ionospheric boundary. This is increasingly being discarded owing to similar modulation periods observed on ground and in the magnetosphere, where twice the period between packets should be observed by ground magnetometers as by the spacecraft.

More recently, mechanisms of generation by Ultra Low Frequency (ULF) wave modulation and standing ion-cyclotron wave interference have been proposed. In the first, standing ULF waves might periodically drive the source plasma into a state of instability, so driving periodic wave excitation [Mursula *et al.* (1997)]. In the second, standing ion-cyclotron eigenmode waves might be generated in the near-equatorial ion-cyclotron resonator created by heavy ion distributions [Guglielmi *et al.* (2000)]. The interference between multiple modes may cause a periodic wave emission from this cavity.

Observations



Spectrograms of He⁺-band pearl pulsations by both Van Allen Probes in conjunction with Halley research station. Wave activity on the ground lasts for over 10 hours in UT, while the spacecraft see small subsets as they pass through the active region during their orbit. Wave activity in the magnetosphere is constrained to the same overall frequency band observed on the ground. Simultaneous poloidal-mode field line resonances are observed by the VA Probes, but at a frequency an order of magnitude higher than the period of the pearl element modulation.



Spectrograms of pearl wave activity observed at Hornsund, Svalbard and on VA Probe-B. The magnetic footpoint of the field line threading the spacecraft at the time of observation was situated over northern Norway, but the waves on the ground have likely experienced ducting along the Ionospheric Alfvén Resonator.

Polarization analysis shows right-hand polarized wave elements just below the He⁺ gyrofrequency line. Inferring a nearly constant frequency band of wave excitation from the ground data, these could originally have been H⁺-band waves that have experienced a polarization reversal at the crossover frequency.

Table 1: Pc1 Pearl Pulsations observed by VA Probes from September 2012 to August 2013

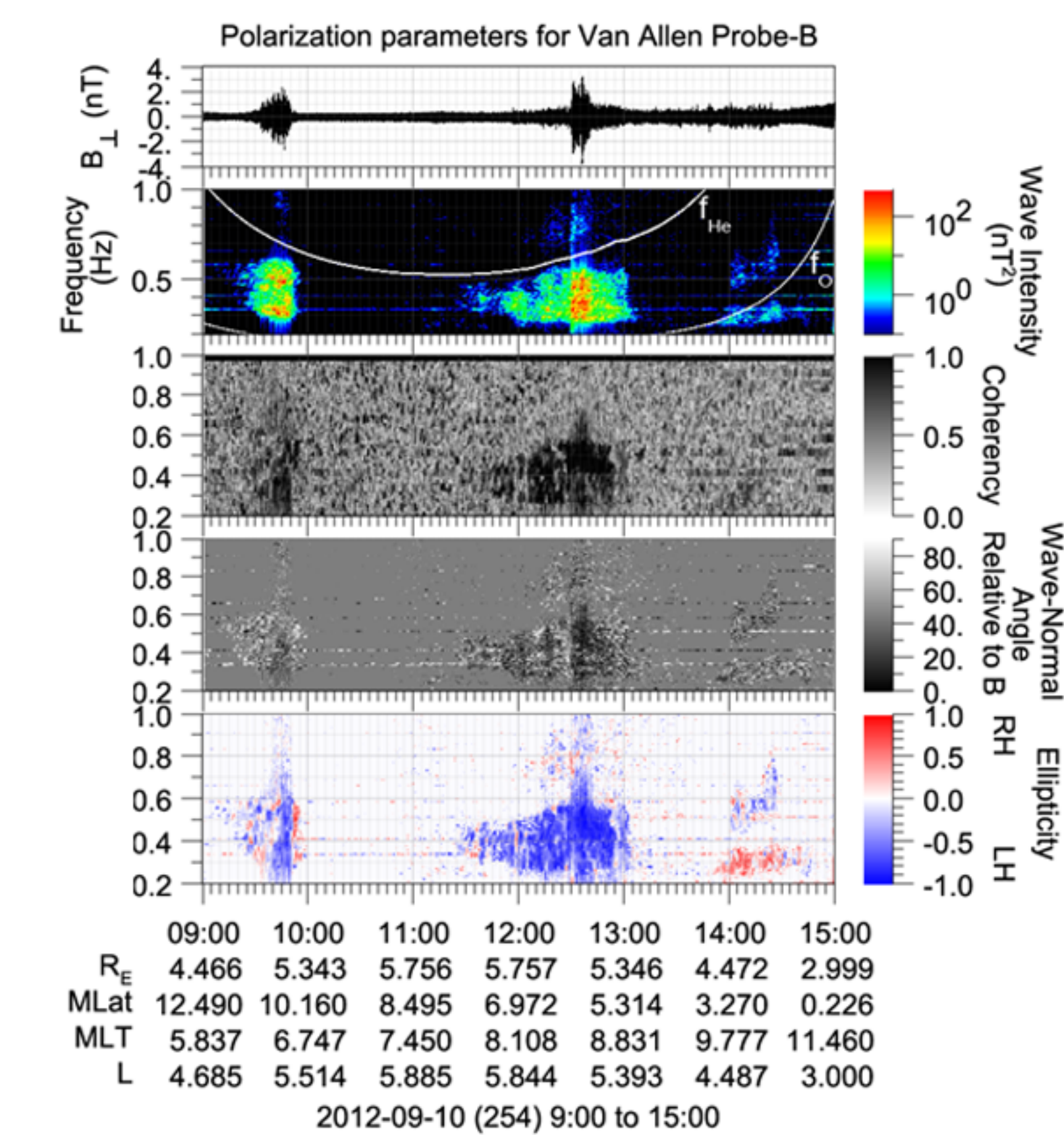
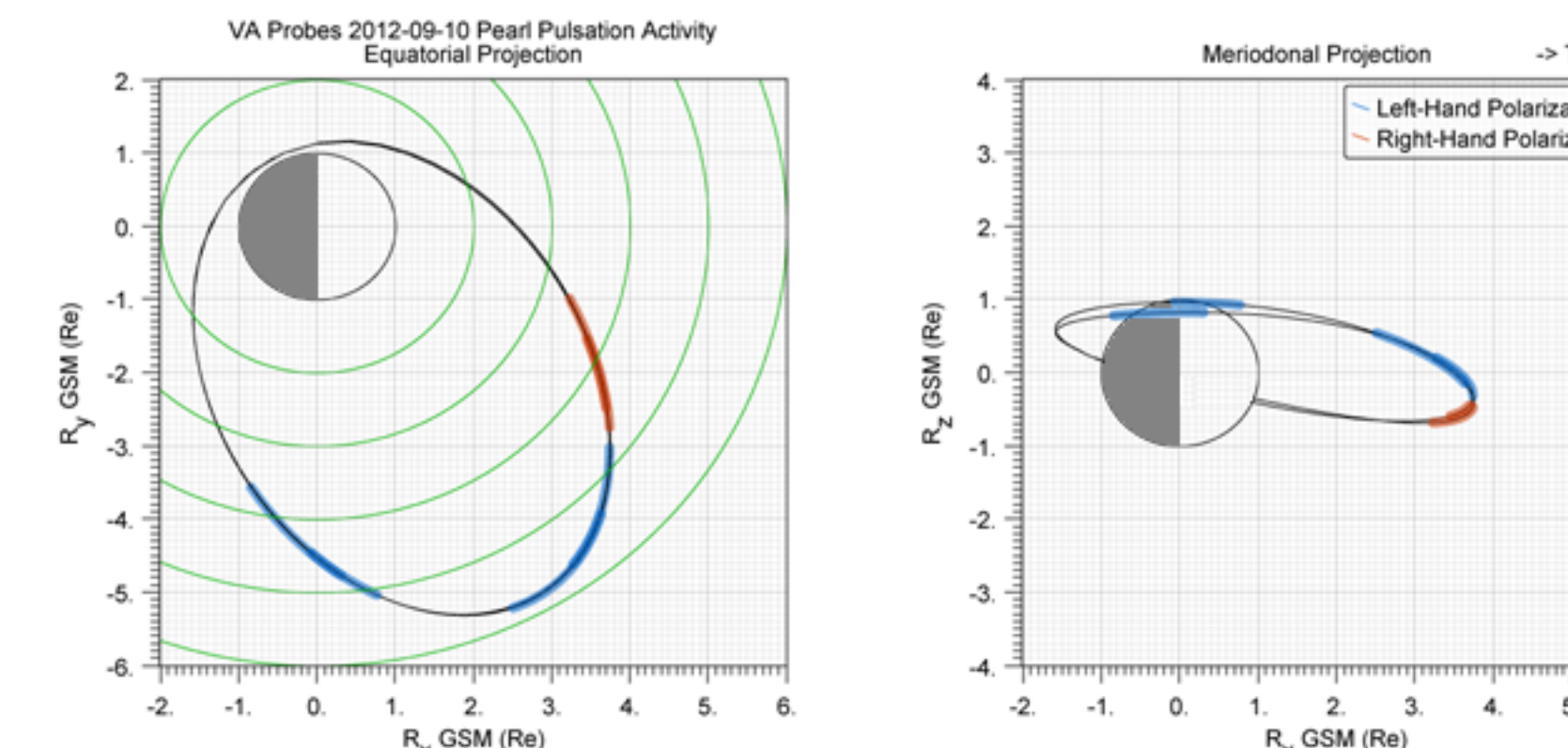
Date	S/C	Time (UT)	Frequency (Hz)	L-Shell	MLT (Hrs)
2012-09-10	A	07:20-08:14	0.38-0.76	4.5-5.0	5.3-6.3
	A	11:05-12:30	0.27-0.51	4.7-5.7	8.3-9.5
	B	09:10-09:55	0.27-0.64	4.7-5.1	6.4-7.1
2012-09-12	A	12:16-12:56	0.82-1.03	2.3-3.6	2.5-4.5
2012-09-13	B	08:45-09:45	0.37-0.66	4.1-5.2	5.1-6.3
	B	13:32-13:48	0.34-0.45	5.8-4.9	9.0-9.2
2012-09-24	B	09:30-11:00	0.22-0.40	5.4-5.8	7.4-8.4
2012-09-27	B	07:12-07:33	0.43-0.54	4.5-4.8	5.3-5.6
2012-10-02	B	17:24-18:54	1.60-3.20	4.2-5.5	8.0-9.5
2012-10-06	A	08:28-09:28	2.50-3.70	2.8-4.4	9.2-11.1
	B	22:08-22:33	0.67-0.77	4.0-4.6	9.3-9.9
	B	23:00-23:32	0.59-0.75	1.9-3.1	10.8-13.0
2012-10-18	B	5:20-6:18	0.8-1.6	2.2-4.1	9.3-12.2
2012-11-06	A	17:50-19:40	1.9-2.7	2.9-5.3	7.3-9.9
	B	17:35-19:20	1.9-2.7	2.9-5.3	7.3-9.8
2012-11-11	B	05:55-06:05	0.65-0.76	5.1-5.3	7.1-7.2
2013-01-23	A	22:52-23:16	0.38-0.47	4.5-5.0	4.1-4.5
	B	22:46-23:34	0.37-0.46	5.2-5.8	3.1-3.8
2013-04-08	A	07:15-08:20	0.56-1.10	5.9-6.0	23.8-0.5
2013-05-29	A	20:56-21:42	0.38-0.47	5.4-5.9	21.4-22.0
2013-07-01	B	16:14-17:28	0.35-0.67	4.8-5.6	21.6-22.7

We have compiled a list of more than 14 Pc1 Pearl events in the first year of observations by the Van Allen Probes. Of these, only two have been observed by both spacecraft, though they occupy similar orbital trajectories. The events exhibiting the greatest wave power occurred in the post-dawnside region, though we have also observed these waves near midnight in MLT. We expect to see more as the spacecraft orbit precesses into the dusk region in the coming months.

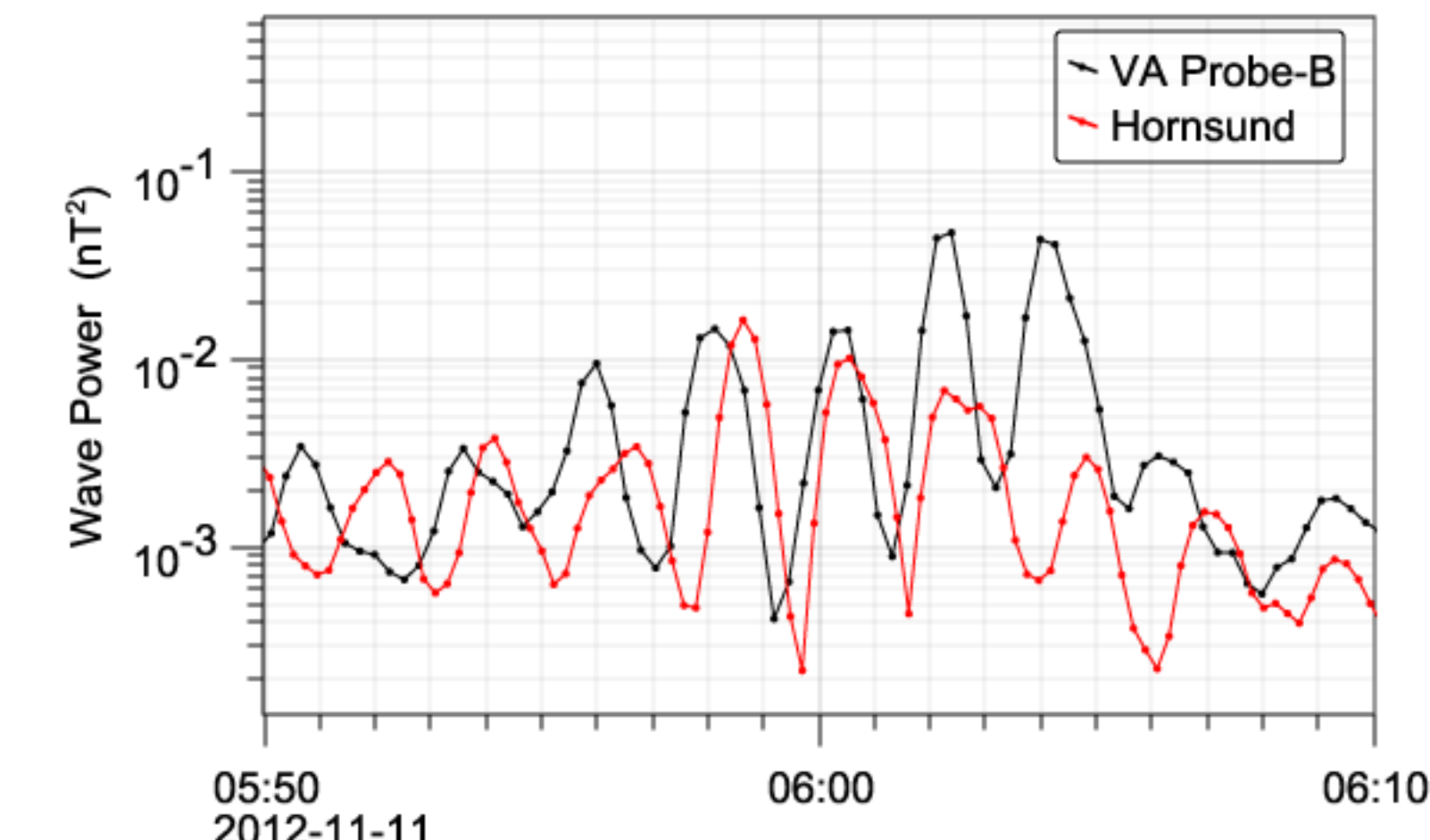
We have a more tentative list of events exhibiting the same L-independent frequency band property as is observed in the events at left, but whose pearl structure is not as clearly defined. This constant excited frequency band could be a property unique to the pearl pulsation subset of ion-cyclotron waves, whose frequency is usually understood to change with the background magnetic field strength.

Analysis

The wave activity on 2012-09-10 appears to follow a central frequency independently from the change in L-shell as the spacecraft travels out of apogee. Once it has crossed the O⁺ gyrofrequency it switches from a strongly left-hand polarized to a right-hand polarized signal. This behavior has been predicted for cases where the wave travels to higher magnetic latitude along the field line to areas of higher ambient magnetic field, increasing the local crossover frequency [Perraut *et al.* (1984)]. However, the Van Allen Probes maintain an equatorial orbit so they should not observe this propagation effect. Possible other causes could include refraction of the right-hand polarized wave at the bi-ion boundary.



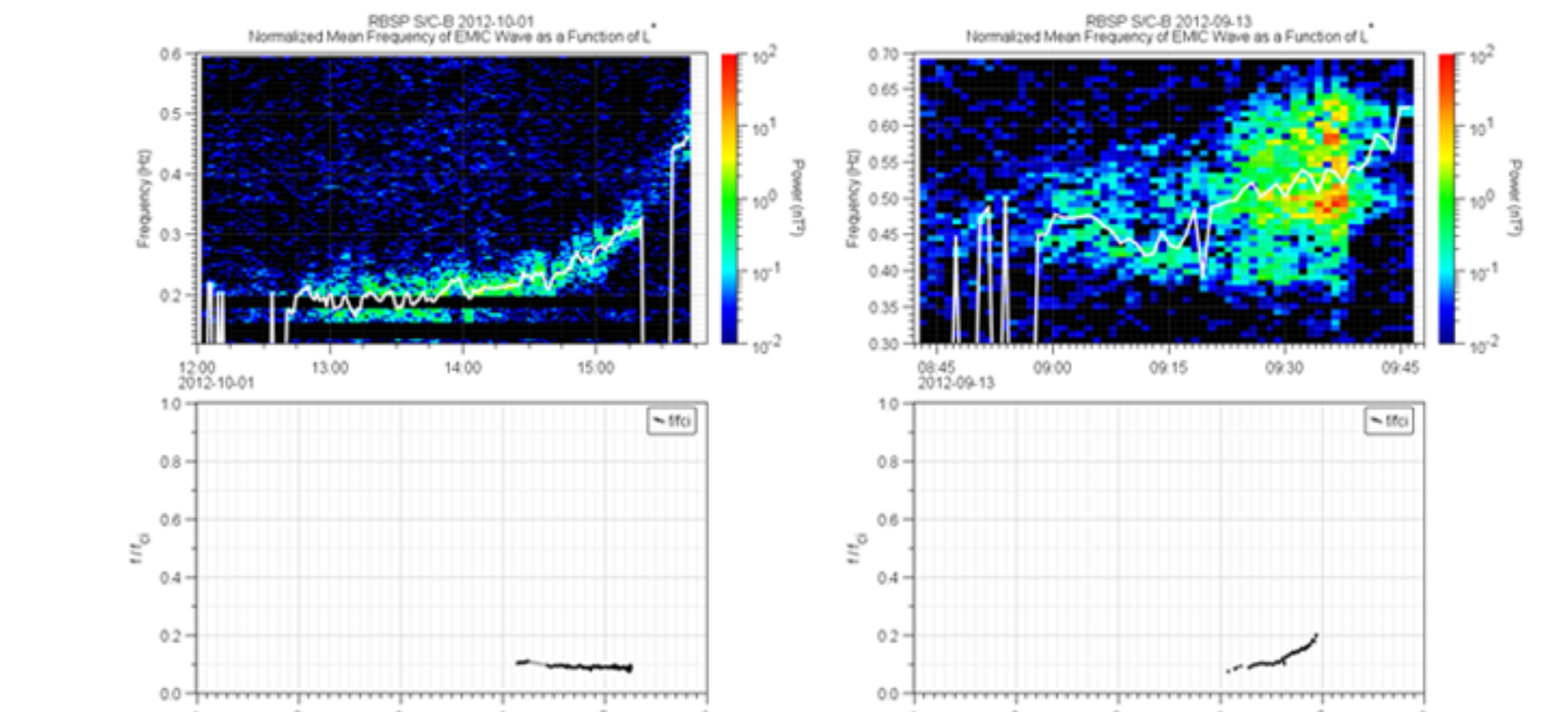
Average wave power over pearl element frequency band for VA Probe-B and Hornsund, Svalbard



At left is shown the average spectral wave power of the wave activity on 2012-11-11 both on the ground and in the magnetosphere. We can see that there is an equal periodicity of wave elements in both locations. The Bouncing Wave Packet theory would predict twice the number of wave elements observed in space as on the ground, as the spacecraft would observe reflections from both ionospheric layers. The consistent ~ 50 second delay between the two observations can be attributed to time of propagation both along the field line and the ionospheric resonator.

Conclusions and Future Work

The Van Allen Probes present a new opportunity to observe pearl pulsations, a class of ion-cyclotron waves that has previously been undersampled relative to traditional EMIC waves. This growing catalog will allow us to further classify their behavior and generation in the magnetosphere. We have confirmed that the Bouncing Wave Packet theory seems insufficient to explain this generation mechanism. The long periods of observed wave activity on the ground suggest an extended azimuthal distribution of a region satisfying EMIC generation conditions, but we cannot discount the contribution of ionospheric ducting to this observation. Both the ULF modulation and ion-cyclotron resonator theories are consistent with the narrow radial extent of the waves as observed in the magnetosphere.



Our next examination of these events will relate to the apparent independence of the central frequency from the cyclotron frequency as the wave activity is observed at different L-shells. Above left we see a non-pulsating EMIC wave excitation whose normalized mean frequency f/f_{ci} is constant in L, while above right the pearl pulsation from 2012-09-13 displays a change in f/f_{ci} with L.

References:

Cornwall, J. M. (1965). Cyclotron instabilities and electromagnetic emission in the ultra low frequency and very low frequency ranges. *Journal of Geophysical Research*, 70, p 61-69
 Guglielmi, A. V., A. S. Potapov, and C. T. Russell (2000). The Ion Cyclotron Resonator in the Magnetosphere. *Journal of Experimental and Theoretical Physics Letters*, 72, p 298-300
 Mursula K., R. Rastkinangas, and T. Bostinger (1997). Nonbouncing Pc1 wave bursts. *Journal of Geophysical Research*, 102, p 17,611-17,624
 Perraut, S., R. Genot, A. Roux, and G. de Villardy (1984). Ion Cyclotron Waves: Direct Comparison between Ground-Based Measurements and Observations in the Source Region. *Journal of Geophysical Research*, 89, p 195-202
 Sucksdorff, E. (1936). Occurrences of rapid micropulsations at Sondankylid during 1932 to 1935. *Terrestrial Magnetism and Atmospheric Electricity*, 41, p 336