Van Allen probes, NOAA, and ground observations of an intense Pc 1 wave event extending 12 hours in MLT

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Introduction

The focus of this talk will be on the EMIC wave event of February 23, 2014, observed by the Van Allen Probes, by proton detectors on the low-altitude NOAA and METOP satellites, and by ground-based magnetometers in Antarctica and Finland.

Key Point: Electromagnetic ion cyclotron (EMIC) waves triggered by large solar wind compressions can be very widespread in the magnetosphere: they can occur over at least a 12-hour local time span, even reaching to midnight, and their width in L can be much wider than that of typical EMIC waves.

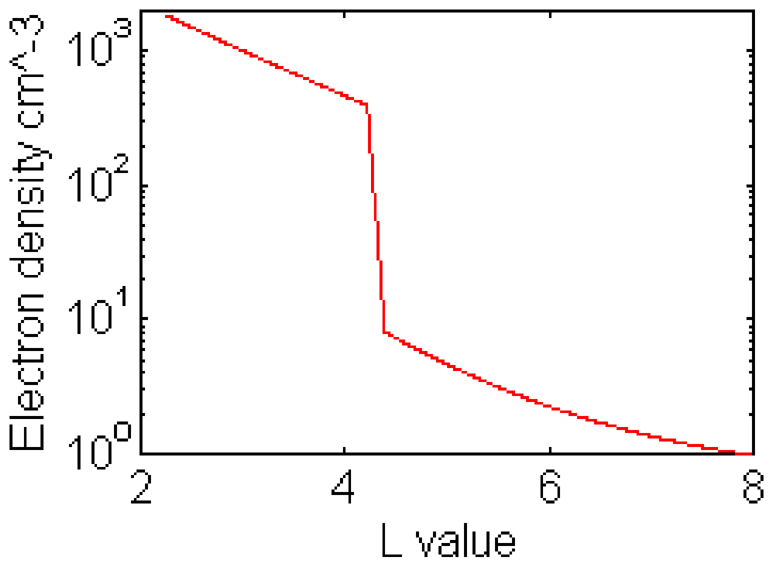
An earlier example in the Van Allen Probes data set is from January 17, 2013.

Two published examples (not shown here), were observed using proxy observations of proton auroras: Zhang et al. [JGR 2008] and Søraas et al. [JGR 2013].

Where are EMIC Waves Observed?

Cornwall [JGR 1965] and Liemohn [JGR 1967] were some of the first to describe how <u>temperature anisotropies in hot electrons and protons were unstable, via cyclotron instabilities, to the generation of VLF and ULF waves.</u>

For various reasons much of the early theoretical and observational effort on ion cyclotron waves was focused on regions near the plasmapause, and "seek and you shall find" worked.



Unfortunately, this focus missed a lot. The early orthodoxy, according to Cornwall et al. [JGR 1970], was that "ring current protons (< 50 keV) … are unaffected by ion cyclotron waves outside the plasmapause."

Later observations showed that waves occurred much more often at higher L shells than in the region of the plasmapause:

- AMPTE CCE – Anderson et al. [JGR 1992] and Keika et al. [JGR 2013]
- CRRES – Fraser and Nguyen [JASTP 2001]
- THEMIS – Min et al. [JGR 2012], Usanova et al. [JGR 2012]

Statistically, there is only a minor enhancement in occurrence near the plasmapause.

Our current understanding is summarized well by Keika et al. [2013]:

<u>Two independent major processes</u> cause EMIC wave excitation in the closed field line region of Earth's magnetosphere.

•One externally triggers H-band waves on the dayside in the outer magnetosphere – because of solar wind compressions.

•The other internally excites He-band waves on the dusk-to-afternoonside in the inner magnetosphere during storm times – because of fresh injections of ions from the plasma sheet into the plasmapause and plume regions.

How are EMIC Waves Observed?

Pc1 waves have traditionally been observed using magnetometers, both on the ground and in space.

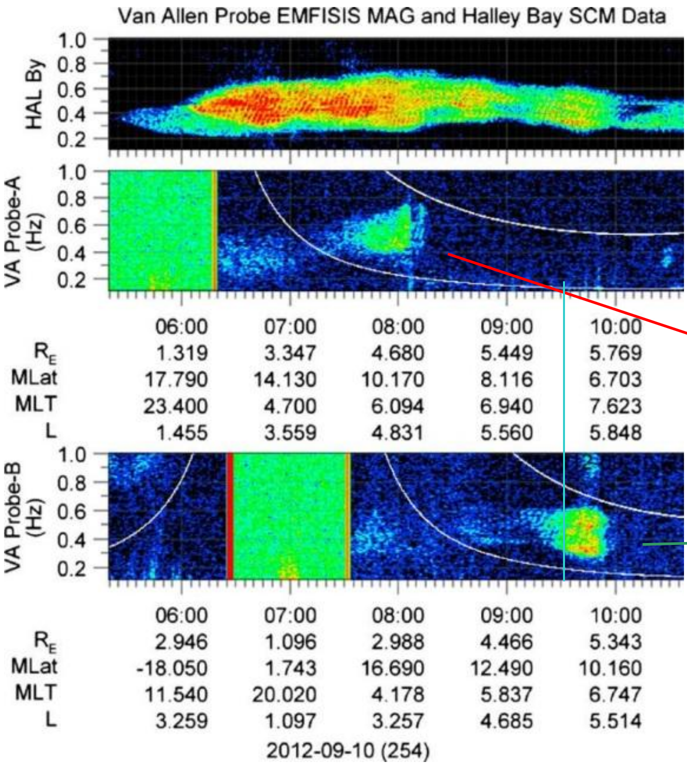
Because a necessary consequence of ion cyclotron wave emission is scattering of hot protons into the loss cone, two additional sensing techniques have become prominent in the past decade:

Proton Aurora Images (IMAGE satellite, ground-based imagers): Immel et al., AGU Mono [2002], Yahnin et al., JGR 2007], Yahnina et al. [JGR 2008], Nomura et al. [JGR 2012]

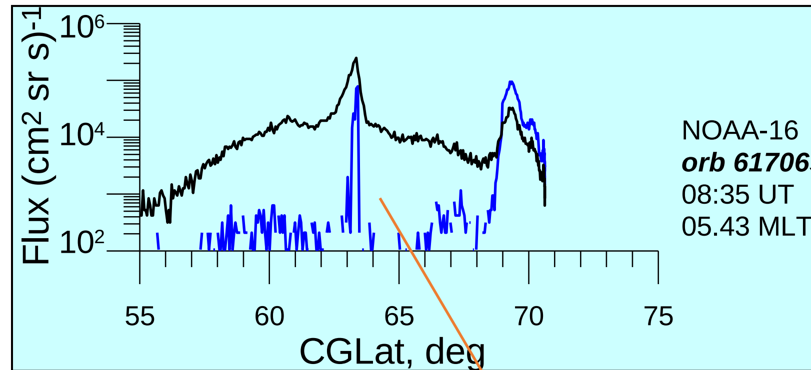
Low Earth Orbit observations of **localized precipitation of ring-current protons** (NOAA POES and METOP): Usanova et al. [JGR 2010], Søraas et al. [JGR 2013].

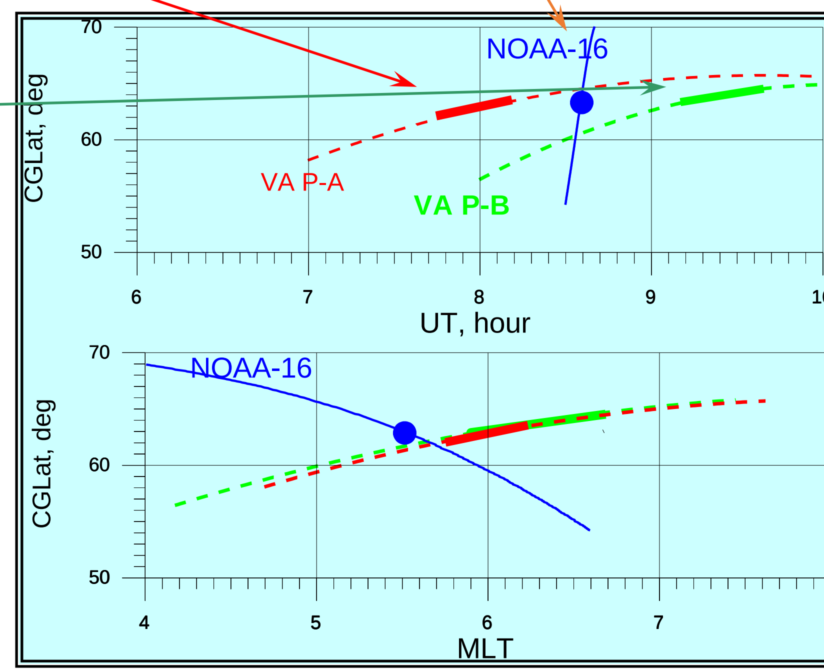
Several recent studies have shown that these three observations (including **magnetometer observations of EMIC waves**) are consistent: Sakaguchi et al. [JGR 2007], Yahnin et al. [JGR 2009].

Localized precipitation of energetic protons (LPEP) and EMIC waves



[*Paulson* et al., GRL 2014]



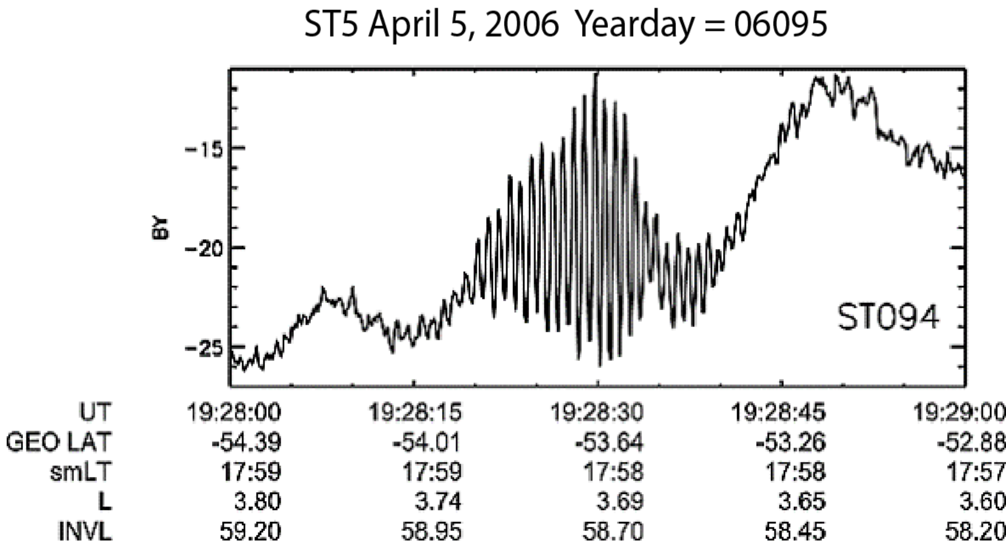


LPEP occurs very near the Pc1 source. This strongly confirms that LPEP is the result of the EMIC interaction.

Slide courtesy of Alexander Yahnin, COSPAR, 2014.

What is the Width in L of EMIC events?

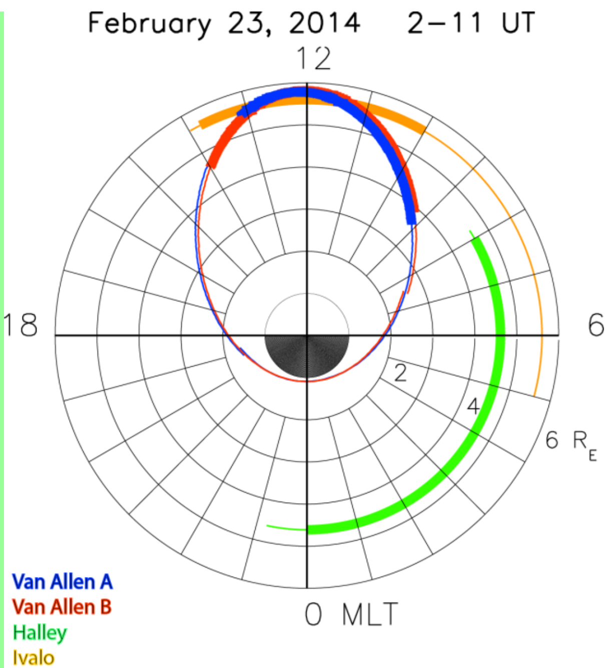
Satellite observations show that the wave generation region is often narrow in L. Observations by MAGSAT [Iyemori and Hayashi, JGR 1989], Viking [Erlandson et al., JGR 1990], and ST-5 [Engebretson et al., JGR 2008] orbit all confirmed this, showing widths often down to ~ 0.1 L.



However, observations from Polar, in a highly elliptical orbit in the outer magnetosphere, at times showed very large widths in L, up to and even exceeding 5 L, during individual passes in the outer magnetosphere [Engebretson et al., JGR 2002]. These much larger widths were observed during solar wind compressions.

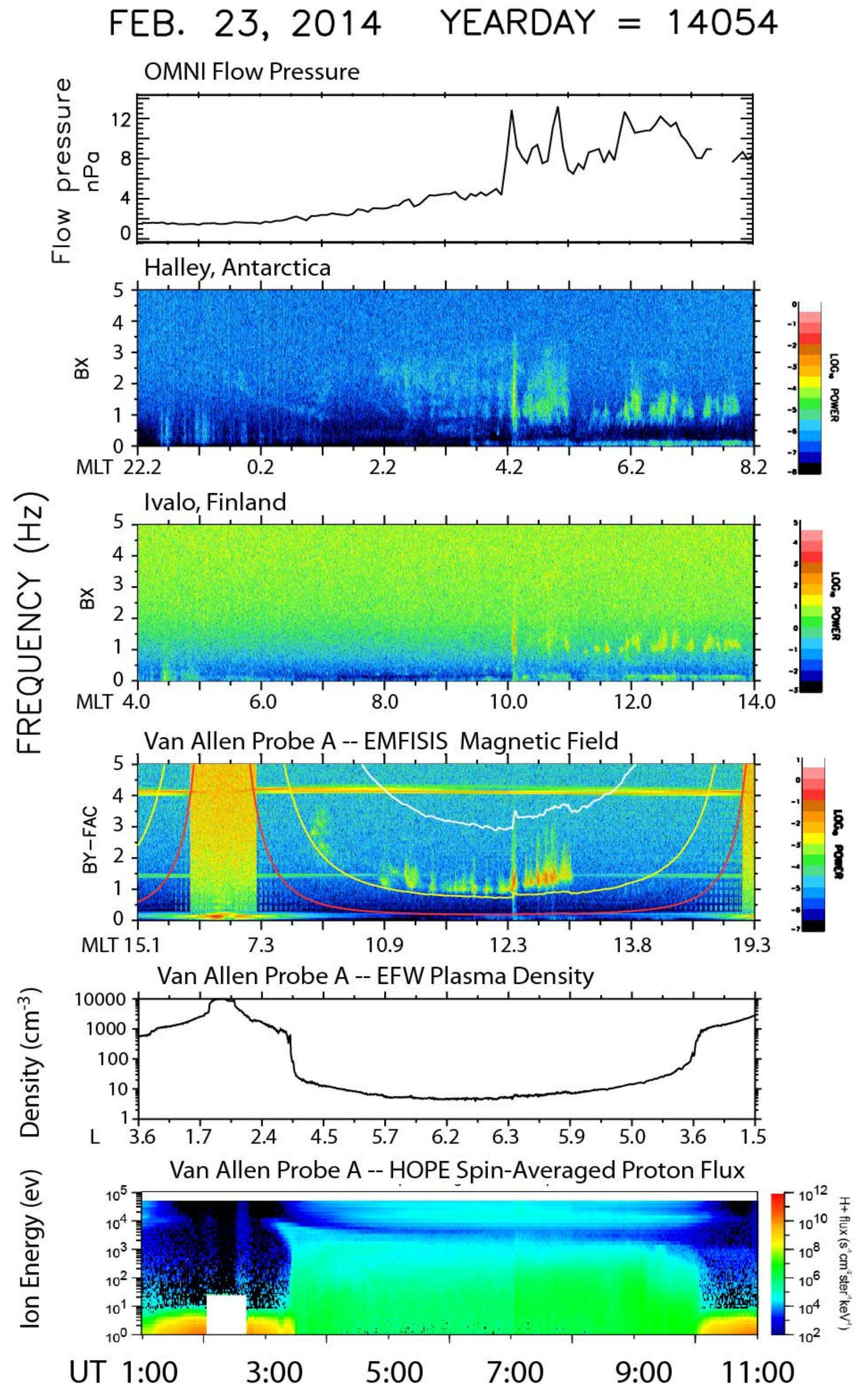
February 23, 2014

A Pc 1 wave event extending over 8 hours UT was observed at Halley, Antarctica Ivalo, Finland, and at both Van Allen probes, in response to a large solar wind pressure increase.



Solar wind flow pressure began to increase near 0230 UT, when the first Pc1 emissions appeared weakly at Van Allen Probe B (~ 9 MLT), just outside the plasmapause, and at Halley (~0 MLT).

Van Allen Probe A, in an orbit ~ 1 hour behind Probe B, first observed Pc1 waves near 0330 UT, when it also passed outside the plasmapause.

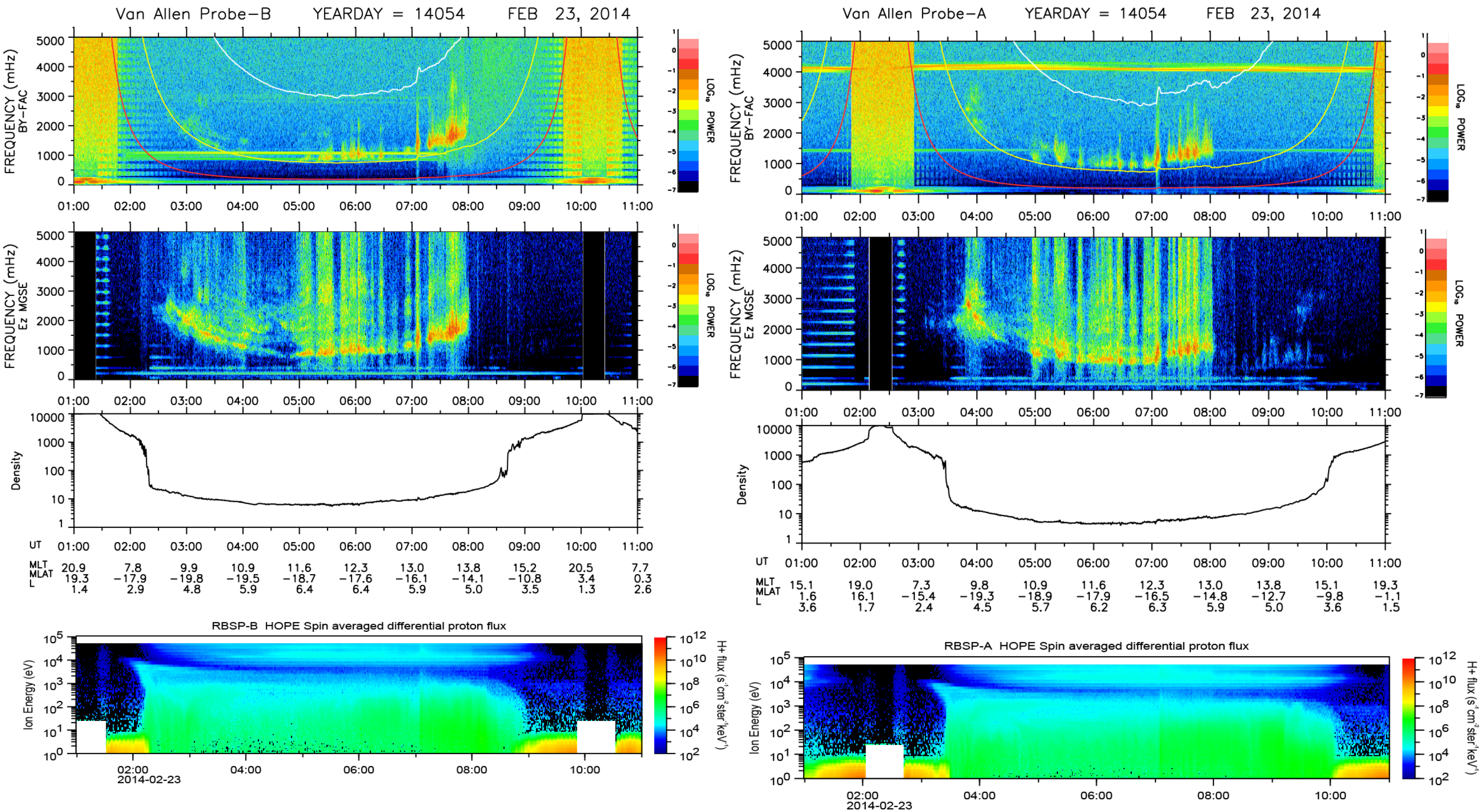


Waves were in the hydrogen band, often just above the He^{+} gyrofrequency (plotted in yellow), but after 0700 UT often filled much of the band from $\Omega_{He^{+}}$ to $\Omega_{H^{+}}$.

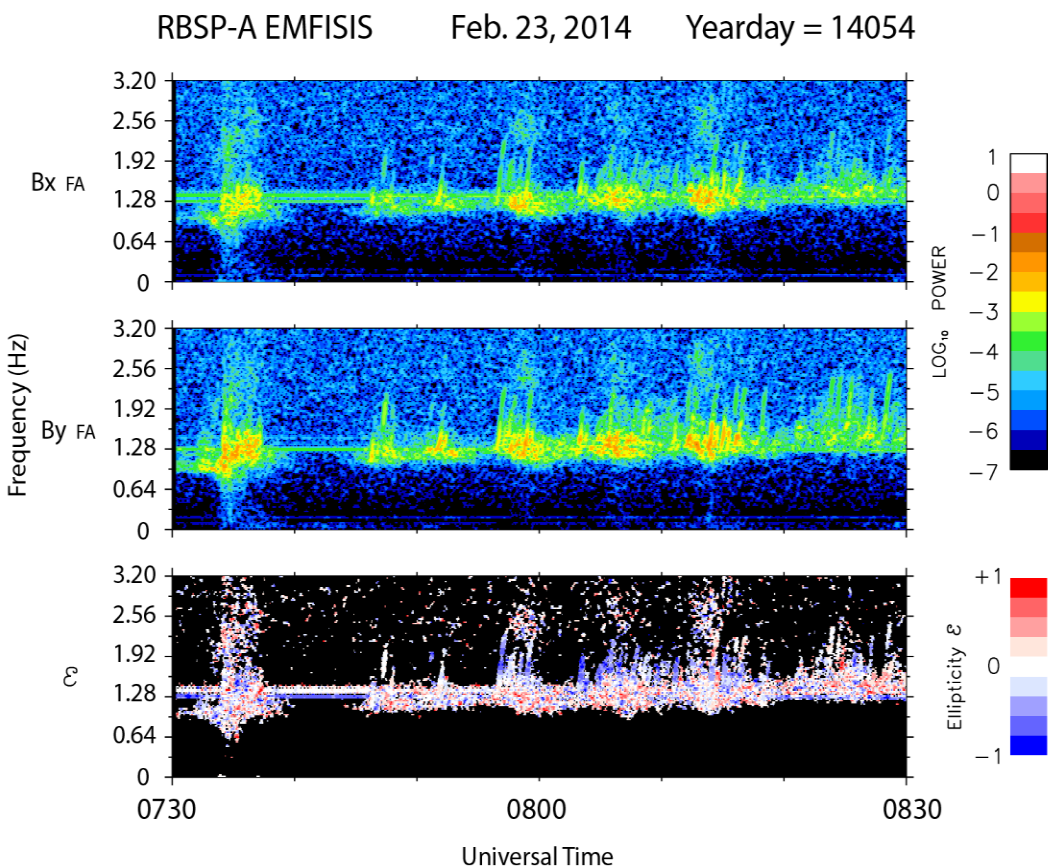
The waves appeared in the L shell range from 4 to 6.4 (apogee).

Low electron density indicates that these waves occurred outside the plasmapause.

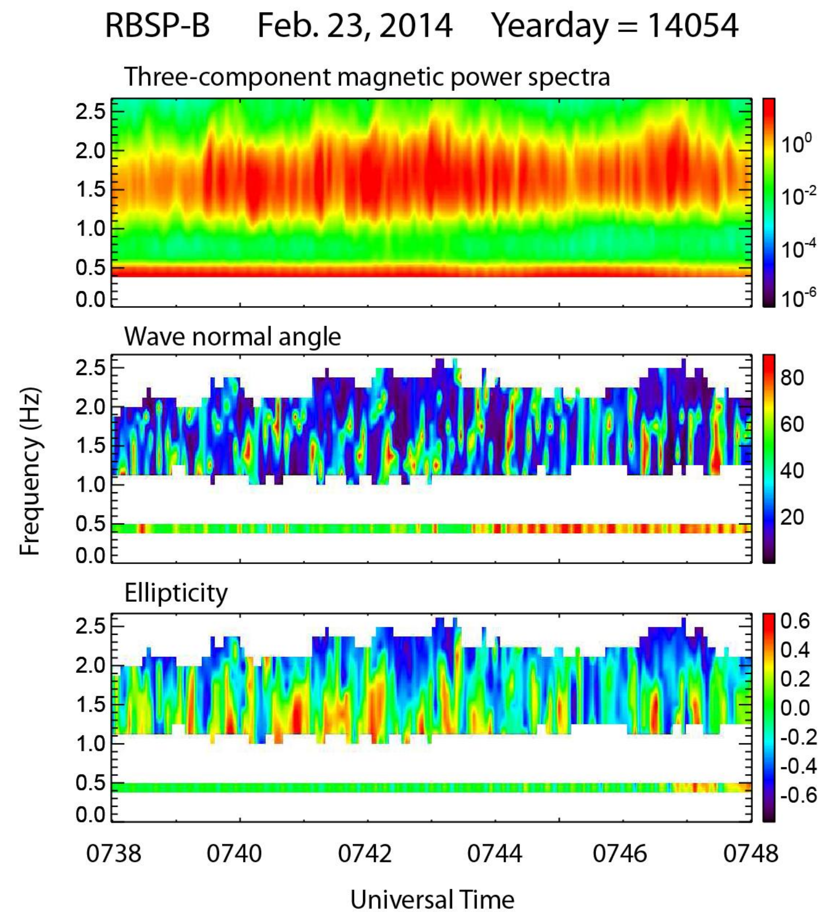
HOPE proton data (bottom panels) showed enhanced ring current fluxes during the event.



Wave amplitudes at both RBSP spacecraft often exceeded 5 nT, and peaked at 12 nT (A) and 10 nT (B). Waves were mostly linearly polarized, but **left-hand polarized triggered emissions** [Pickett et al., GRL 2010, Omura et al. JGR 2010] were observed at both spacecraft when the waves were most intense.



A closer look (10 min) reveals much fine structure in the wave normal angle and ellipticity.

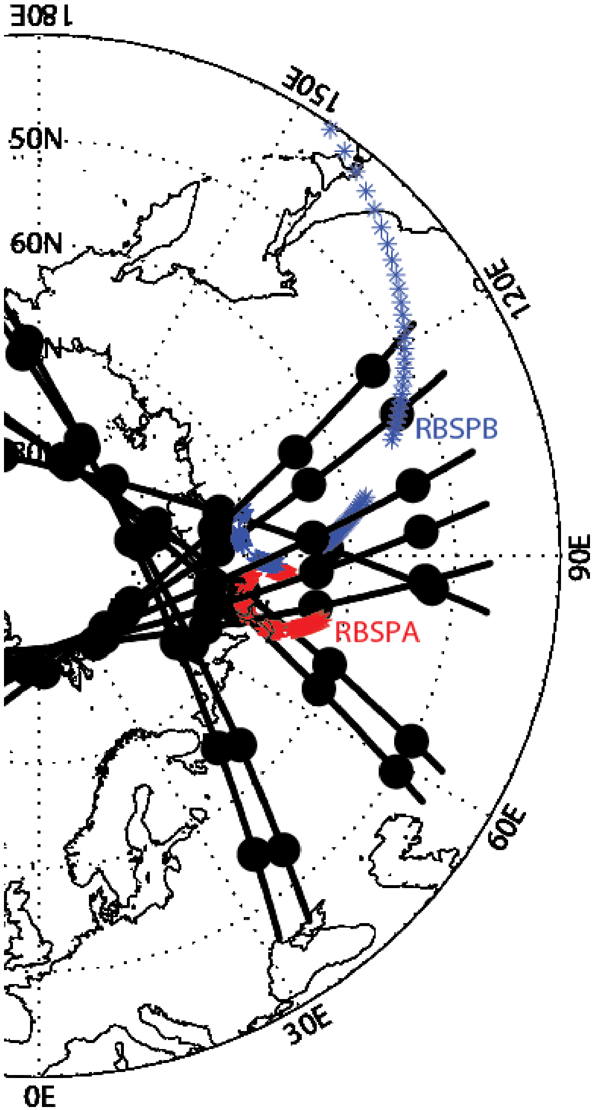


plot courtesy of Lei Dai, Univ. of Minnesota

POES / METOP Observations

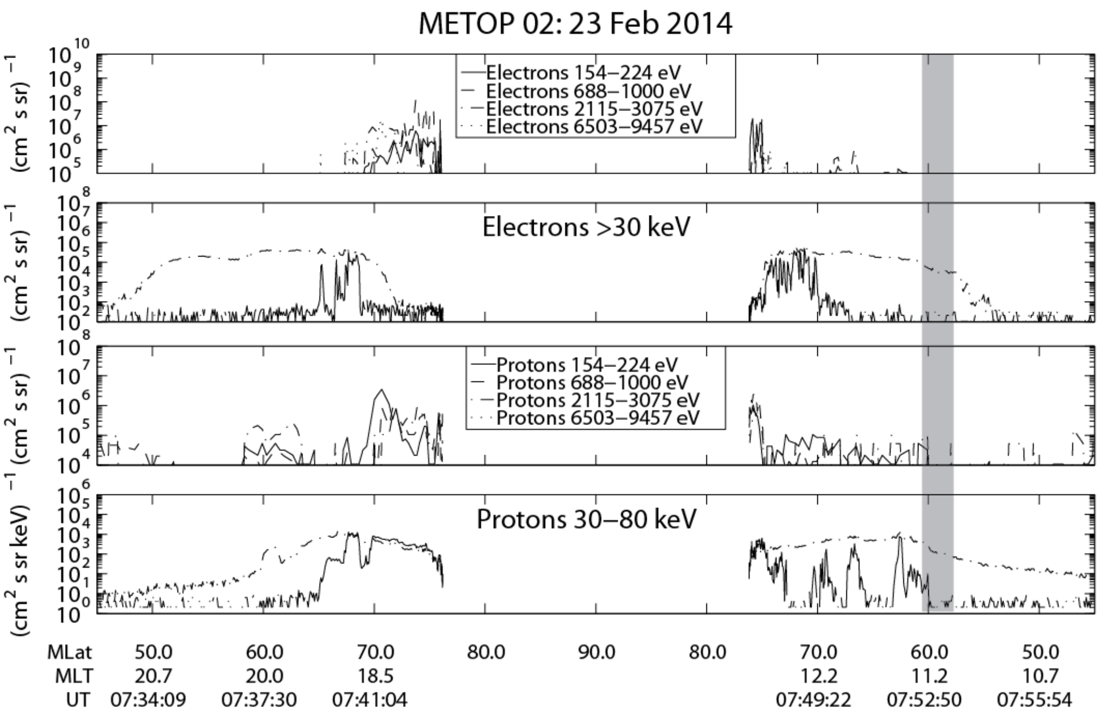
Ten passes of NOAA and METOP spacecraft over the northern hemisphere region near the magnetic footpoint of the RBSP / Van Allen Probes provide proxy information on the L-shell extent of the EMIC wave region, via observations of precipitating 30-80 keV protons.

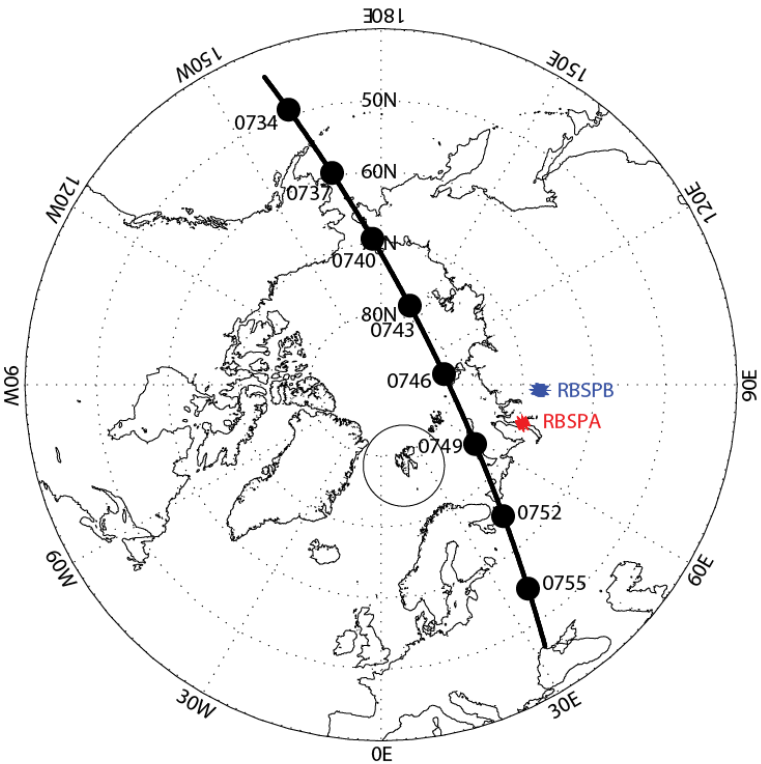
The plot at right shows all footprints (in geographic coordinates) for NOAA/METOP and Van Allen Probes (RBSP).



METOP 7:52 UT

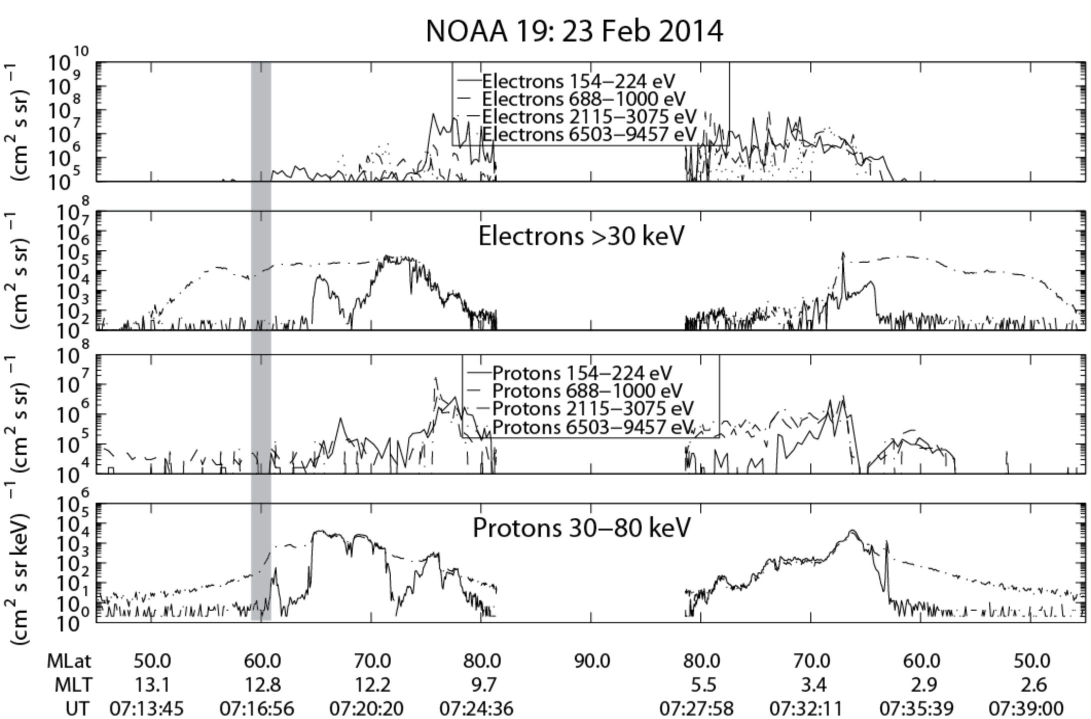
METOP passed equatorward ~ 1 hour MLT west of the magnetic footpoints of RBSP-A and B, and observed precipitating 30-80 keV protons in three latitudinal bands from 70° to 60° MLAT. The gray shading shows the approximate MLAT of RBSP-A and B.

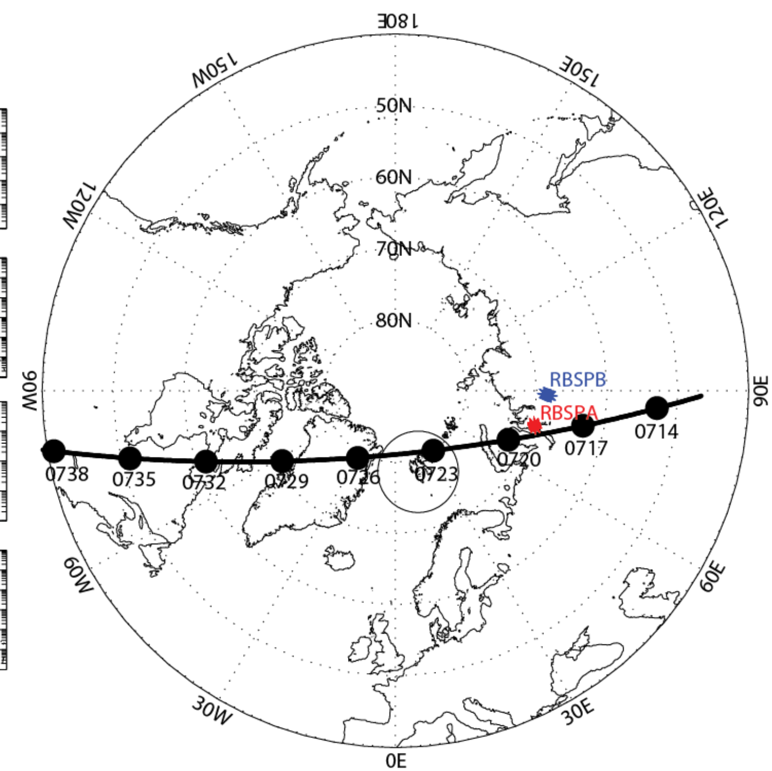




NOAA 19 7:17 UT

NOAA 19 passed poleward very near the magnetic footpoints of RBSP-A and B, and observed precipitating 30-80 keV protons in one narrow band at 61°, near the MLAT of RBSP-A and B (gray shading), and a broad band from 64° to 72° MLAT.



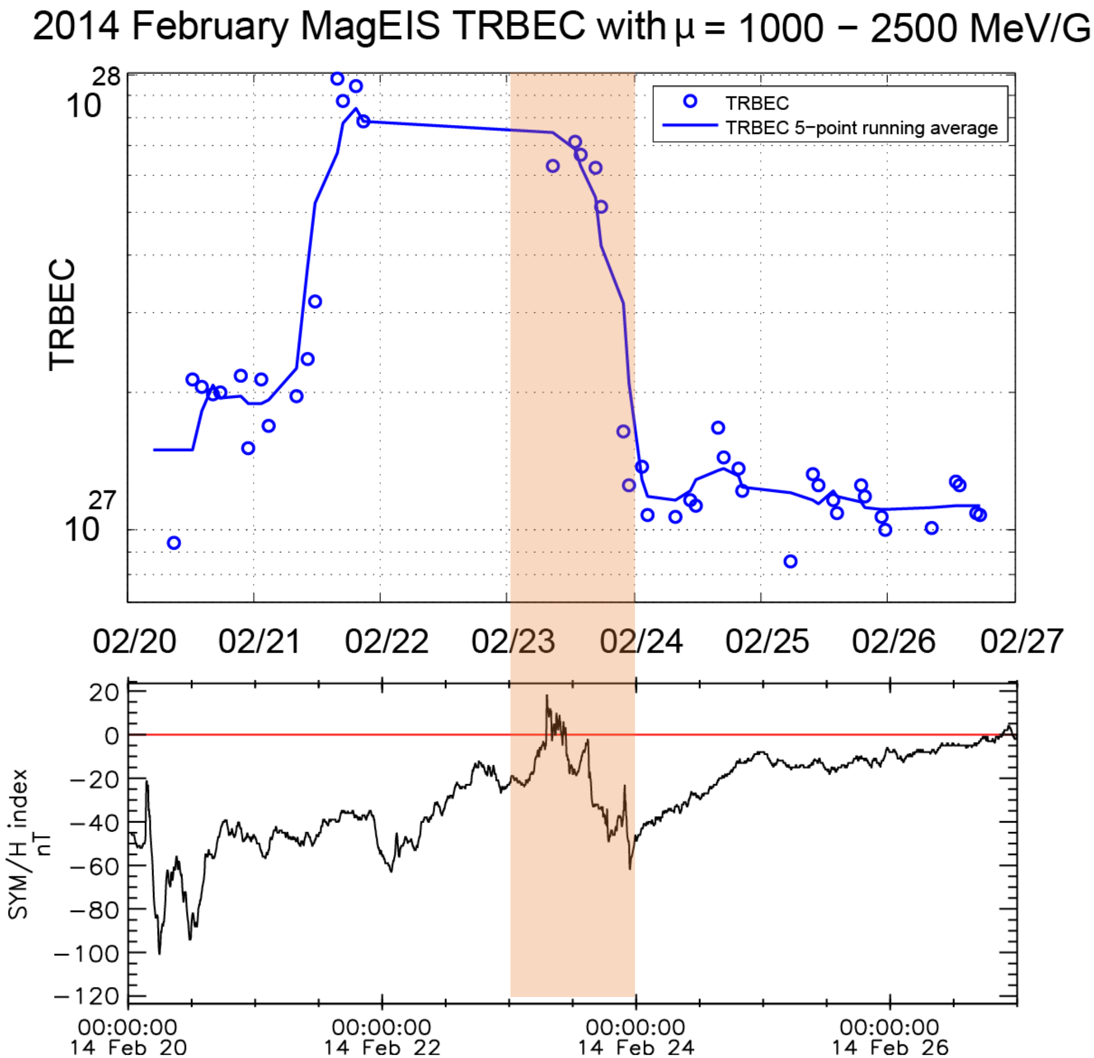


Effects on Radiation Belt Electrons

The upper plot at the right shows <u>total radiation belt electron content </u>(TRBEC) using MagEIS data. The μ range shown, 1000 to 2500 MeV/G, corresponds to ~1.2 - 2.5 MeV at L* = 4.5.

Unfortunately, there was a data gap on Feb. 22, but <u>a clear drop of TRBEC is shown during the second half of Feb. 23.</u> This occurred <u>after</u> the large increase in SYM-H, during the main phase of a small storm.

Plot courtesy of Chia-Lin Huang, University of New Hampshire.



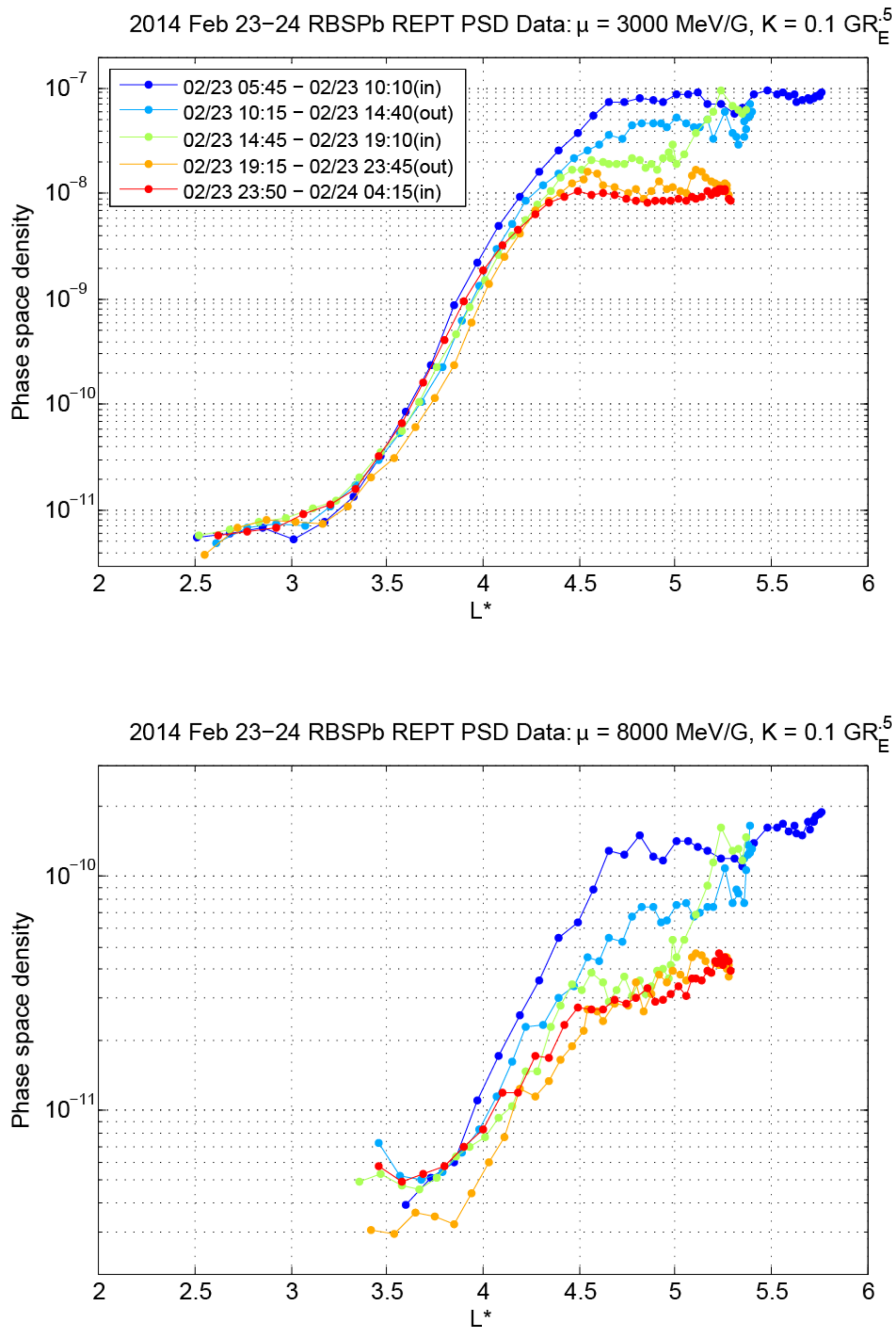
REPT Phase Space Densities

In this figure, each line is phase space density on an outbound or inbound pass, colored with time as labeled in the upper panel. The upper panel is for lower energies (~3 MeV at L=4.5) and the lower panel is for higher energies (7-8 MeV at L=4.5).

The two populations have different L profiles as a function of time. For the first 3 passes, the higher energy's L profile between L= 4.5 and 5 decreases rapidly to a much lower value than the original level. Notice the higher energy's L profile doesn't change much after the 3rd pass, perhaps due to the lack of EMIC waves.

On the other hand, the lower energy's L profile continues to decrease. This may be caused by other, storm-related mechanisms.

-- Plots courtesy of Chia-Lin Huang

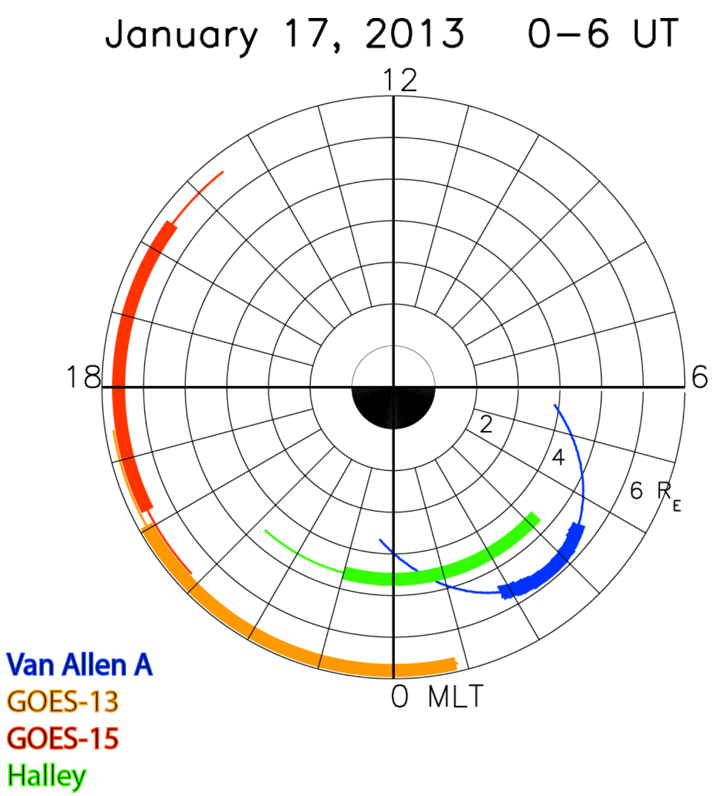


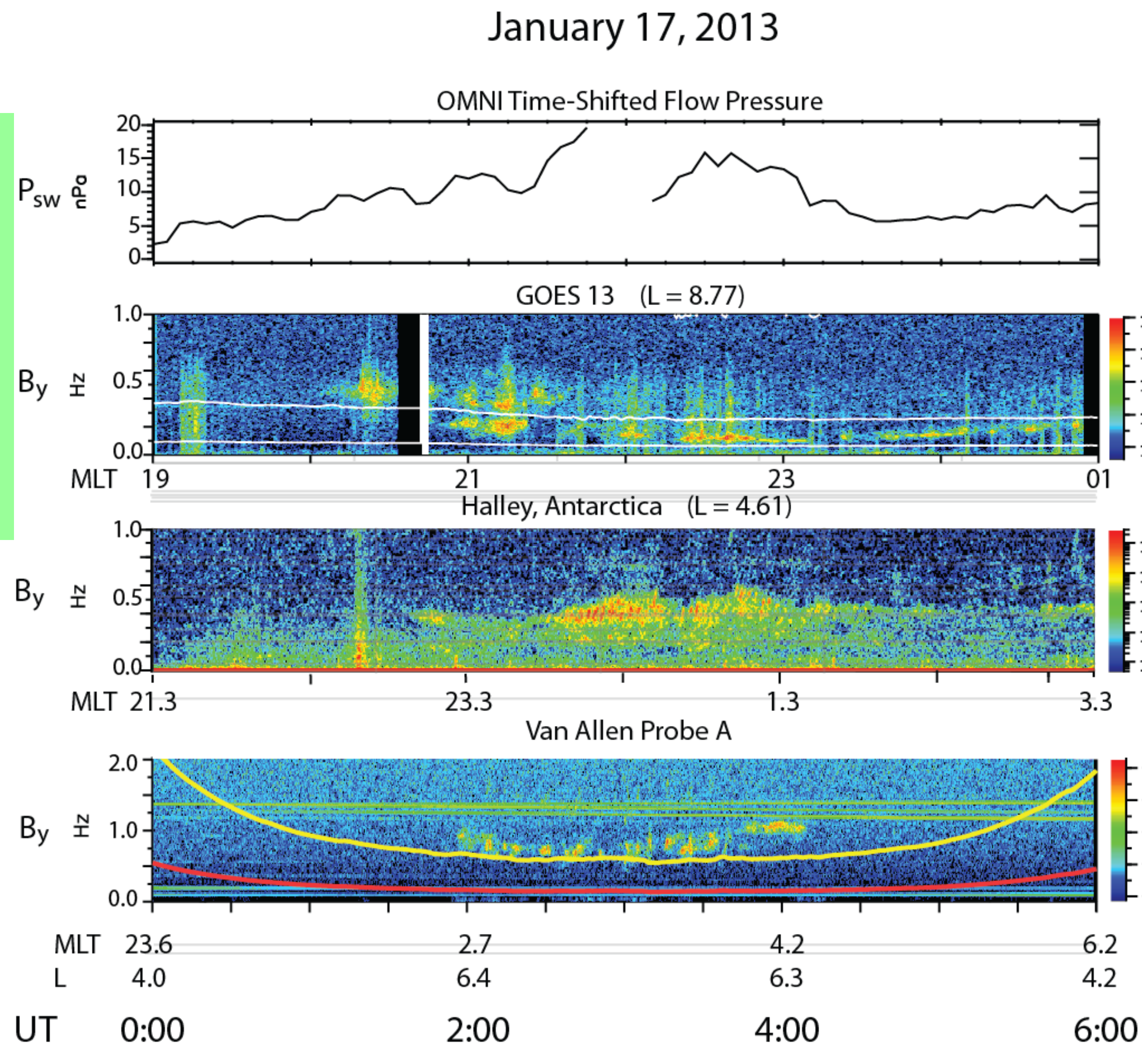
Summary

- EMIC waves stimulated by large solar wind compressions can appear over wide ranges of both local time and L shell.
- The EMIC wave event of February 23, 2014 is the longest-duration and most intense event we have yet observed with the Van Allen Probes. The wave activity was stimulated by a gradual 4-hour rise in solar wind pressure, and subsequent sharp increases.
- Its local time extent was ~14 hours (from midnight to nearly 14 MLT).
- NOAA POES and METOP data show that its radial extent was broad: from 2 to at least 4 L shells. Also, the bandwidth observed at Halley was wider than that observed at RBSP, again suggesting wave generation across a range of L shells.
- The combination of these factors suggests that this wave event might have a significant effect on electrons in the outer radiation belt. Preliminary analysis of particle data from RBSP is consistent with this … but more detailed analysis is needed!

January 17, 2013

EMIC waves were detected across about 10 hours in MLT and 4 L-shells on the nightside, at GOES 13/15, Halley, and both Van Allen Probes from ~0200 – ~0400 UT. Peak amplitudes at RBSP-A,B were 2.5 nT and 3 nT, both near 3 MLT.





Energetic electron precipitation was detected by all three BARREL balloons at times during this interval. It was most intense near geosynchronous orbit (at balloon 1G), simultaneous with waves seen at GOES-13, RBSP-A and Halley.