Energetic Electron Penetration Into Inner Radiation Zone

J. F. Fennell[1], D. L. Turner[1], S. G. Claudepierre[1], J. B. Blake[1], J. L. Roeder[1], C. Kletzing[2], S. G. Kanekal[3], A. N. Jaynes[2], J. H. Clemmons[1]

1. The Aerospace Corporation, Los Angeles, CA
2. University of Iowa, Iowa City, IA
3. Goddard Space Flight Center,

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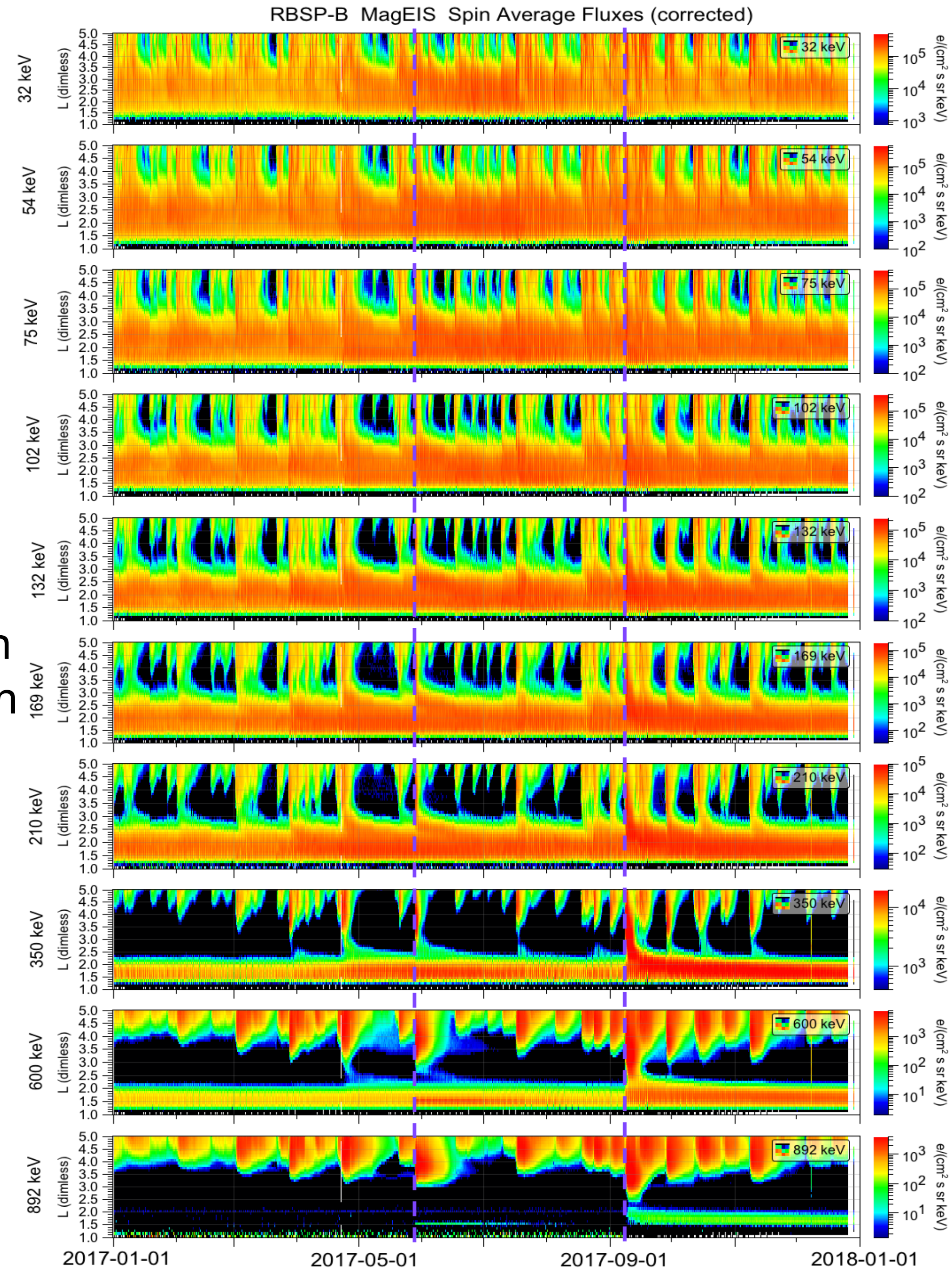
Overview of Presentation

- Set stage by showing an overview of the MagEIS data for 2017
- Provide IMF conditions for the May and September 2017 storms
- Show the Van Allen Probes orbital configuration for both storms
- Examine the response of 25-200 keV electron fluxes and pitch angle distributions to the storm activity at low L* near perigee and compare them with the EMFISIS wave observations for both storms
- Show the response of 32-900 keV electrons to the both storms at two fixed L*, 1.55 and 2.05
- Summarize the similarities and differences of the electron responses at low L* near perigee for the two storms
- If time, show the response at lower energies to the September 7 interplanetary shock that traversed the magnetosphere
- Summary

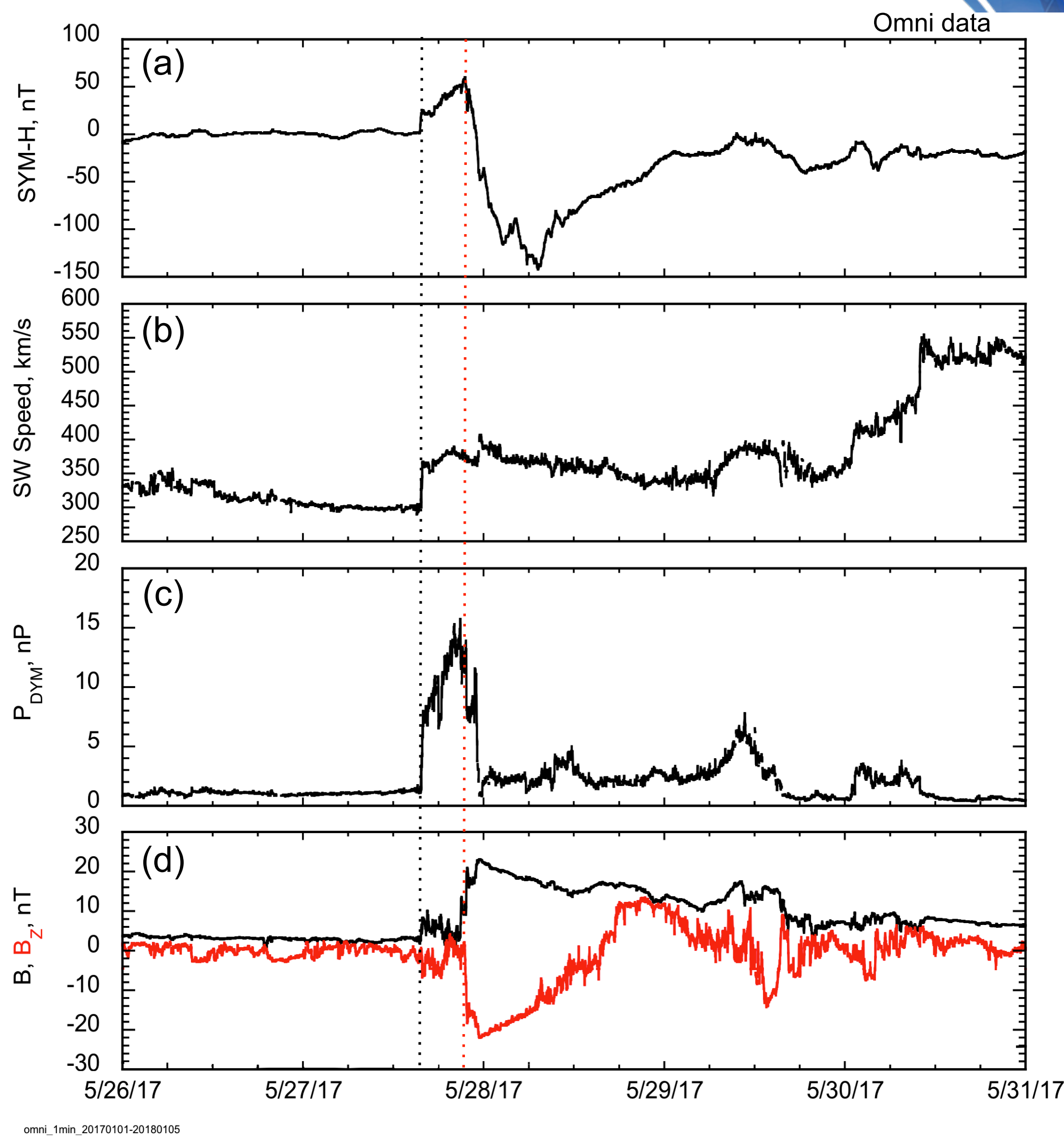
Electron Fluxes in 2017

- Each panels is an L versus Time plot for the electron flux at a constant energy as labeled on the left axis
- The L range is from 1.1 to 5
- The fluxes are color coded using the right hand color scales
- The dynamical changes in the fluxes are obvious in this display
- For the current study we will focus on the magnetic storm events starting on 27 May and 7 September as marked by the dashed purple lines
- *Note that at 892 keV there are residual fluxes at low L that survived the conservative automated corrections applied to the data to remove the penetrating proton responses as discussed by Claudepierre et al., 2015, 2017.*



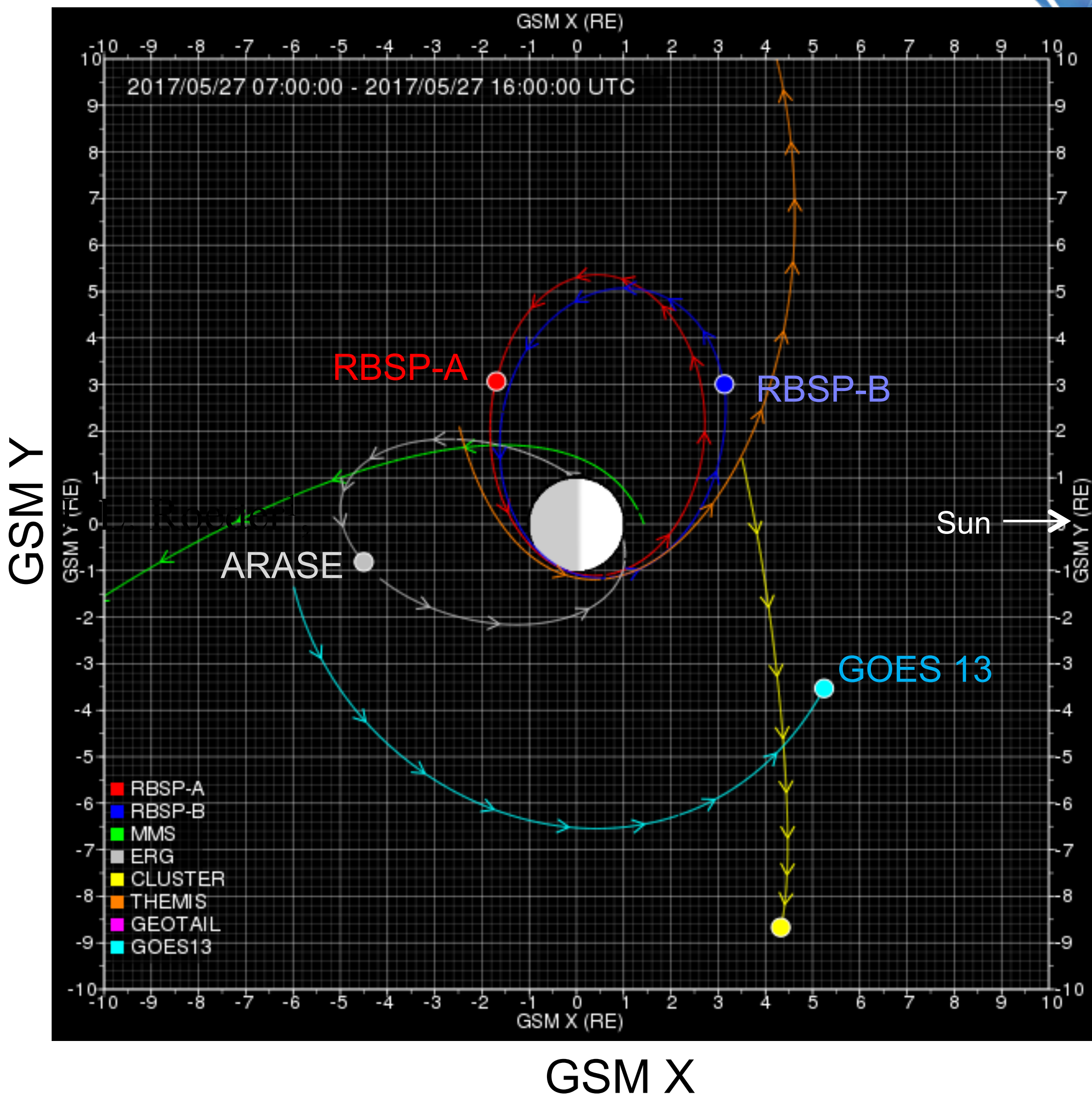
Conditions for the May 27, 2017 storm event

- The storm started late on 27 May in response to a jump in the solar wind pressure (panel c) and a strong southward turning of the interplanetary magnetic field (panel d)
- The initial dynamic pressure pulse, associated with an interplanetary shock arrival, caused an SSC (panel a).
- The dynamic pressure (panel c) continued to rise for about 6 hours.
- The interplanetary field (panel d) turned strongly southward as the pressure started to fall
- SYM-H (panel a) started falling as Bz turned southward (panel d)
- The solar wind speed (panel b) was low to moderate throughout the event



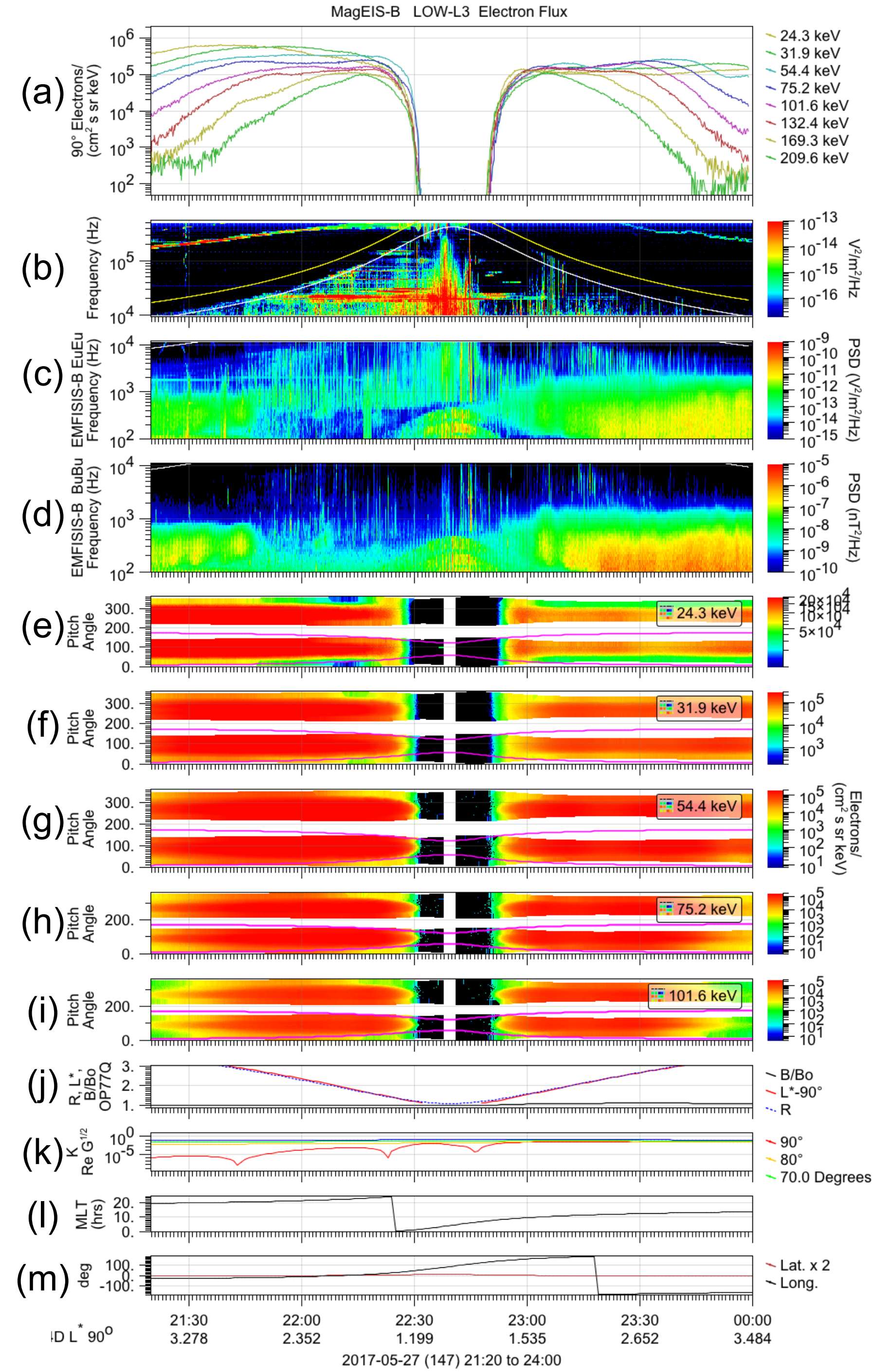
Orbital Configurations for 27 May 2017 at 16:00 UT

- The Van Allen Probes (RBSP-A and RBSP-B) were on opposite sides of their orbit plane during the periods of interest, passing through perigee about 5.5 hours apart
- The RBSP-A and -B apogees were in the dusk sector
- The other satellite orbits are shown for reference and the results will not be discussed here



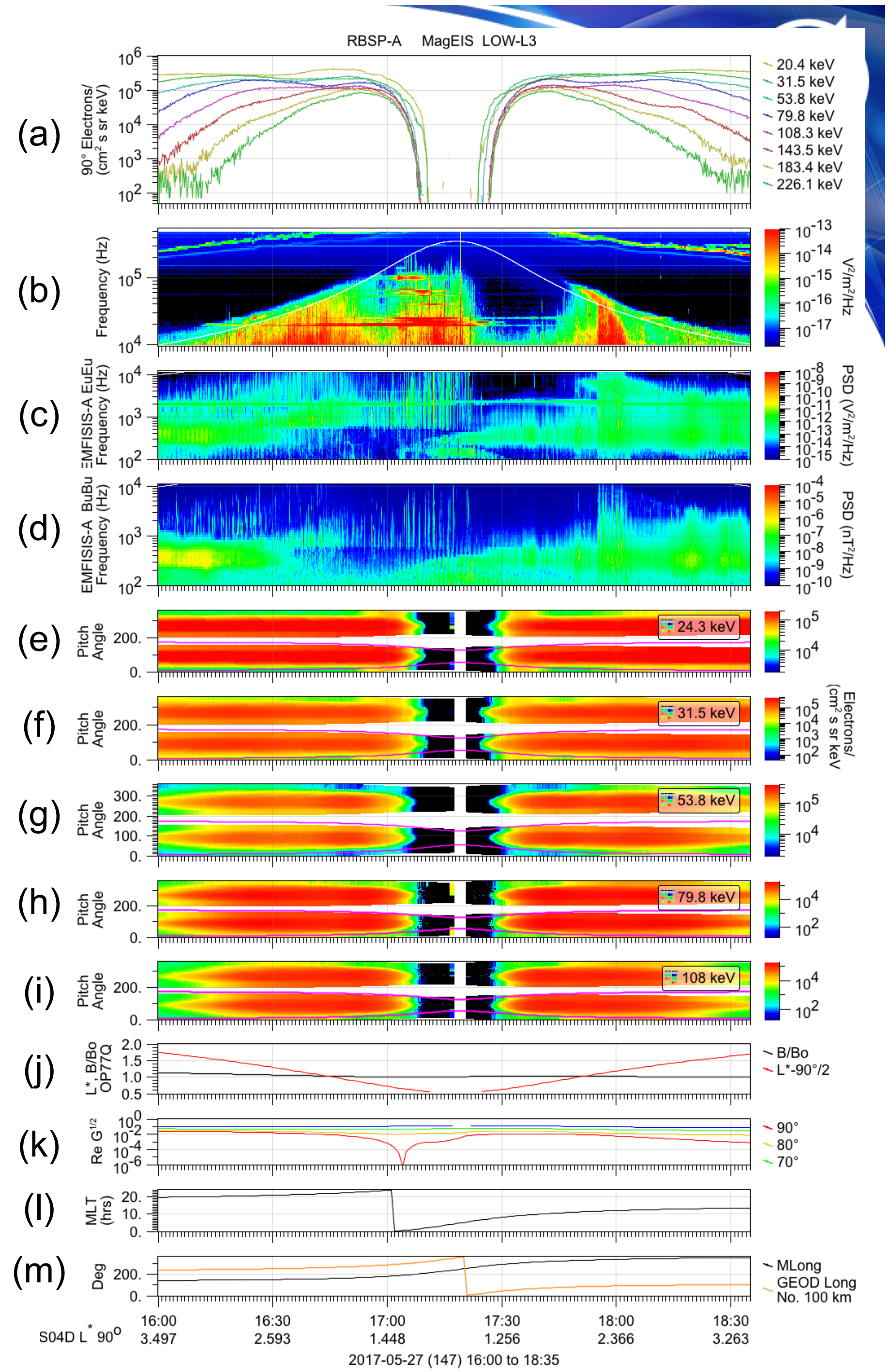
RBSP-B Electrons and Waves 27 May 2017 near 22:35 UT

- RBSP-B traversed perigee near 22:35 UT providing a pre storm baseline for the particle distributions and waves in the slot and inner zone
- Panel (a) shows line plots of the ~24-210 keV electron fluxes
- Panels (b)-(d) show the wave data from EMFISIS for 100 to 5x10^5 Hz with (b) covering the upper frequencies and (c) & (d) covering the electric and magnetic component of the VLF frequencies respectively
- Panels (e)-(i) show the pitch angle distributions for a selection of electron energies as labeled in the panels
  - Magenta lines mark the drift loss cone angle
- Panels (j)-(m) show a variety of reference parameters such as L*, B/Bo, K, MLT, Latitude and Longitude corresponding to the satellite’s position in magnetic and geographic coordinates



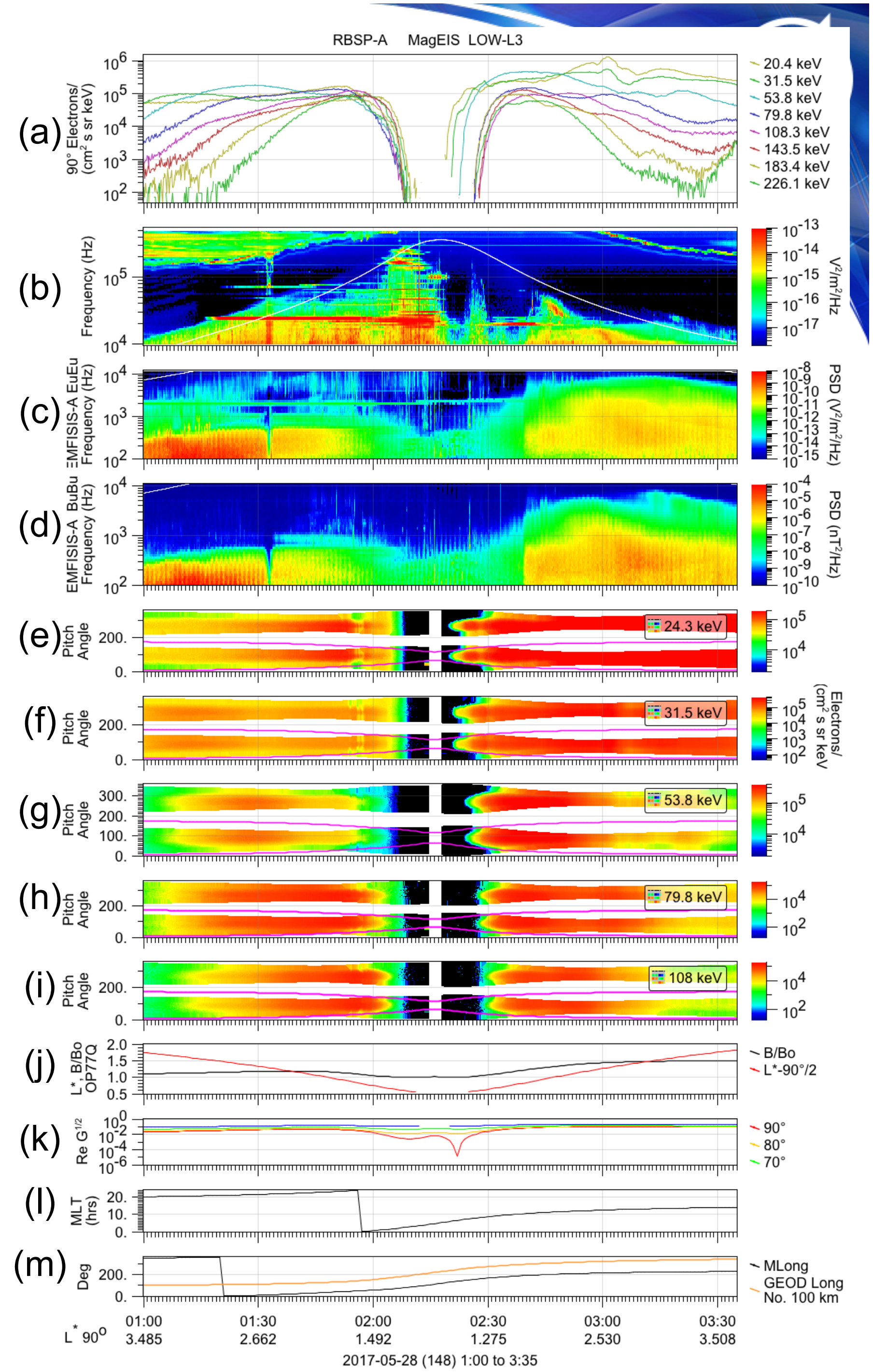
RBSP-A Electrons and Waves 27 May 2017 near 17:20 UT

- Like the previous plot but with pre storm data from RBSP-A
- The white line in the wave panels is ½ fce (1/2 the local electron cyclotron frequency)
- The intense emission in panel (b) near 20,000 Hz is most likely a ground based transmitter signal
- Only four energies displayed as pitch angle distributions (panels (e)-(h))
  - *The magenta lines correspond to the drift loss cone angle*
- For this and the preceding slide, the electron flux profiles are smooth and undisturbed
- Pre storm, the electron angular distributions were pancake (normal) distributions at all local times both at RBSP-A and RBSP-B



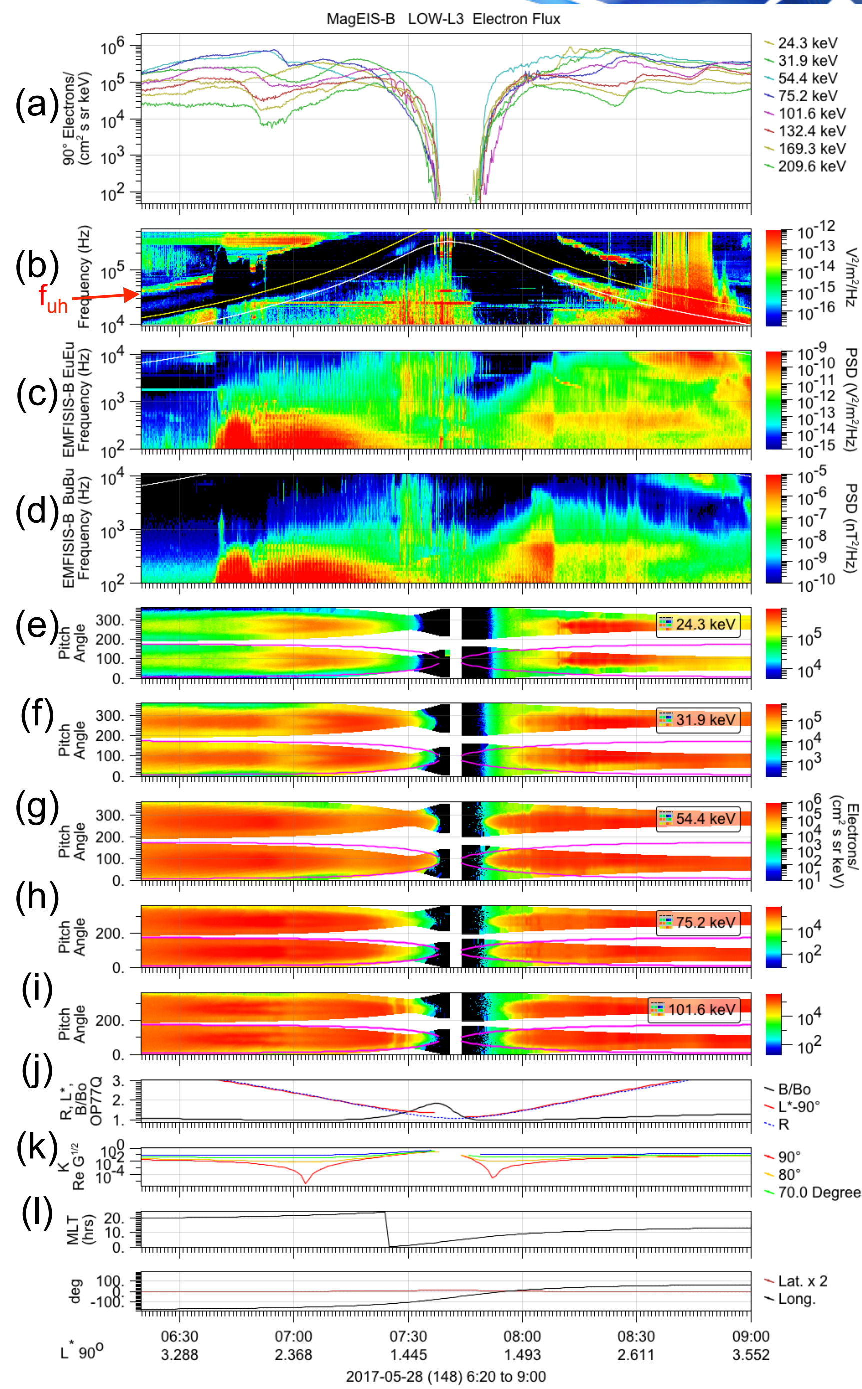
RBSP-A Data During Storm Main Phase at 01:00-03:35 UT 28 May

- The electron fluxes near perigee have ragged profiles
- The ≤108 keV fluxes are definitely enhanced around 03:00 UT and L*~2.5 compared the same L* in previous RBSP-A traversal
- The ≤53.8 keV fluxes have penetrated to lower L* near 02:20 than in the previous traversal
- This indicates the electrons are being radially transported to lower L* and the fluxes are rising
- The pitch angle distributions in panels (e) & (f) show significant and non uniform narrowing near 01:50 UT, indicating that some rapid losses had occurred at those energies
    - *Compare those angular distributions to the earlier pre storm distributions*



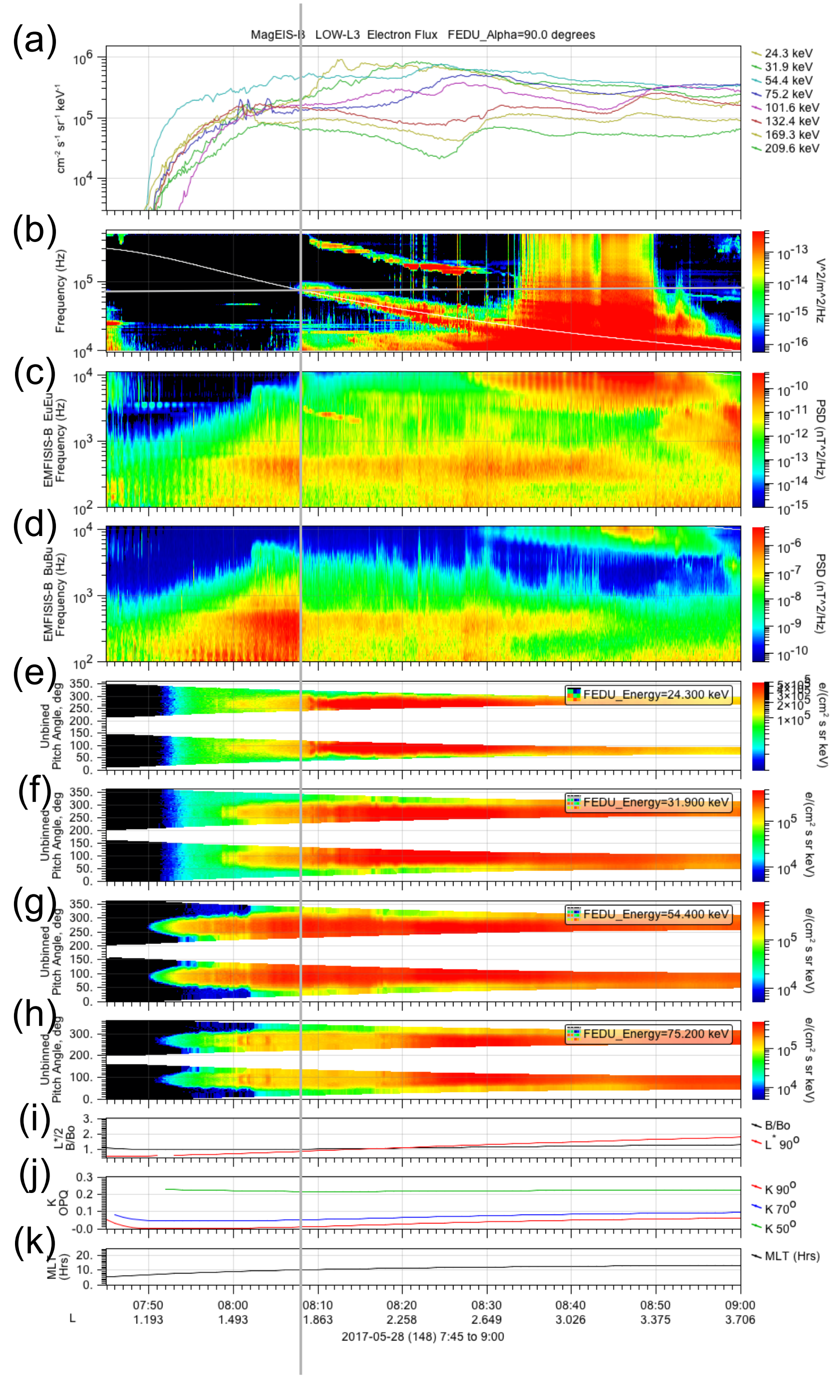
RBSP-B Data During Storm Main Phase at 06:30-09:00 UT 28 May

- These data were taken near the end of the storm main phase
- The 90°electron flux profiles near perigee show the effects from injection/transport and losses
- The wave data shows what looks like strong chorus-like emissions to low L* near 08:00-08:30 UT
- The crossing of the plasmasphere boundary is evident in the upper hybrid line in panel (b) near 06:45 on the dusk side but not on the morning side where the chorus-like emissions were observed
- There is evidence of modification of the 24.3 keV electron angular distributions at the lowest L* of the chorus-like emissions near 08:10 UT in panel (e)[also next slide]
- The other energies also show evidence pitch angle distribution modifications (e.g. near 07:00 and 08:00 UT)



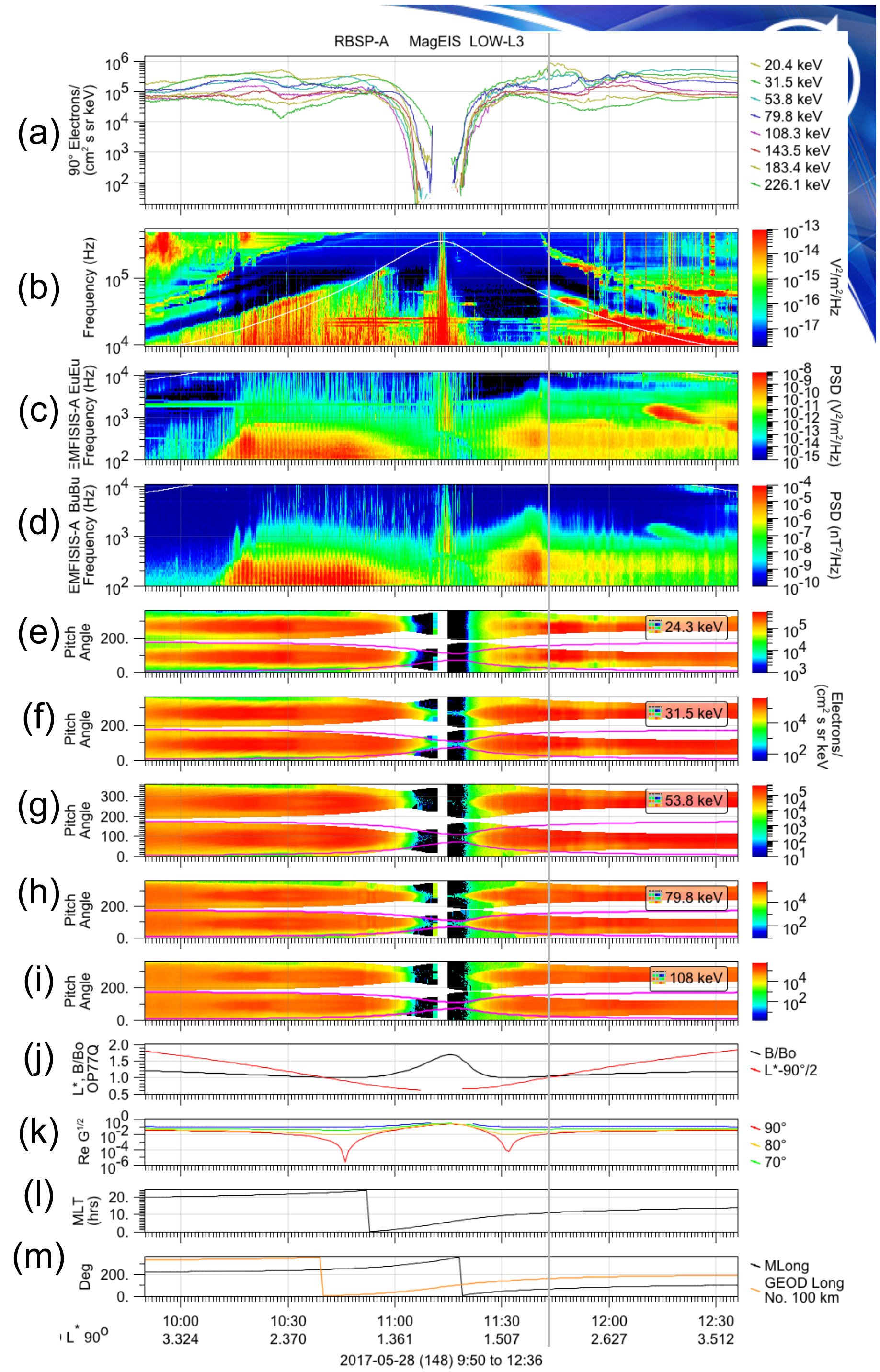
RBSP-B Data During Storm Main Phase - expanded view of outbound traversal from perigee

- Note the structure in these low energy fluxes in panel (a) and in their corresponding pitch angle distributions in panels (e) through (h)
- It is clear there are strong and probably rapid changes occurring both in pitch redistribution and in radial transport that give rise to the flux structures observed here
- Chorus emissions appear to be occurring at L*<2
- The radial density profile appears to be smooth, based on the UH waves until they go off scale
- In general, the wave emissions are strong throughout the pre noon region shown
- The traversal occurred close to the magnetic equator (i)



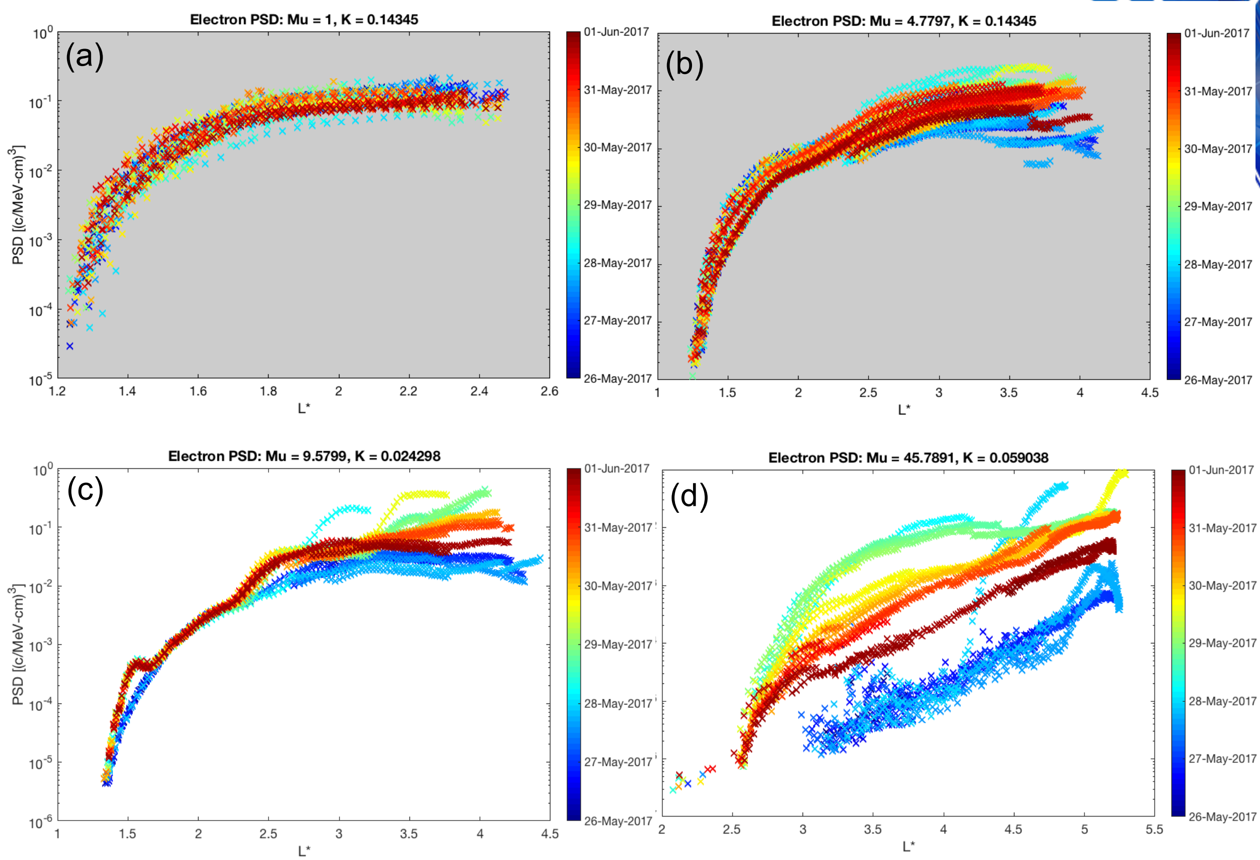
RBSP-A Data During Storm Early Recovery Phase at 09:50-12:35 UT 28 May

- In early recovery some of the structure of the flux profiles near perigee was reduced
- During this traversal there are weak fluxes at 90° pitch angle that traverse the full perigee interval, especially in panels (f) and (h)
  - *This indicates that these electrons could drift around the Earth without being lost*
- Again we observed chorus-like emissions to low L* values on the dayside (MLT<12) with corresponding structure in the pitch angle distributions indicative of patchy electron loss
- On the dusk side we observed "butterfly" angular distribution
- In this case the plasmapause appears to be near L*=2 on the dayside outbound just at the inner edge of the chorus emissions

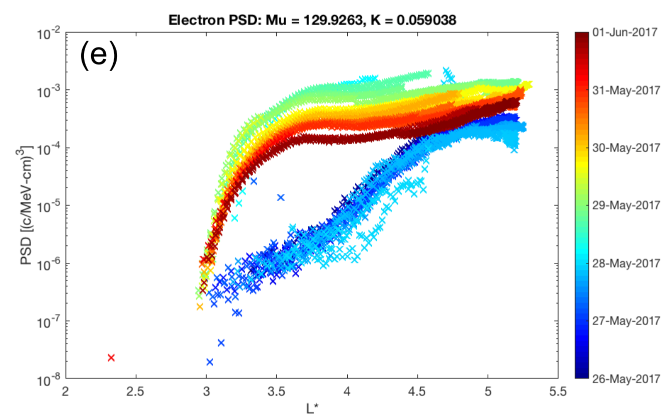


PSD Radial Profiles For Fixed Mu and K

- Examples of radial profiles of the phase space density (PSD) at selected first (Mu) and second (K) adiabatic invariants are shown in panels (a)-(e)
- The dates are color coded with the pre storm times in blue and post onset in green through red
- Panel (a), for the lowest Mu, shows only small or no increase in PSD over the L* range for this storm
- Panel (b) shows PSD increase for L*>2.5 only

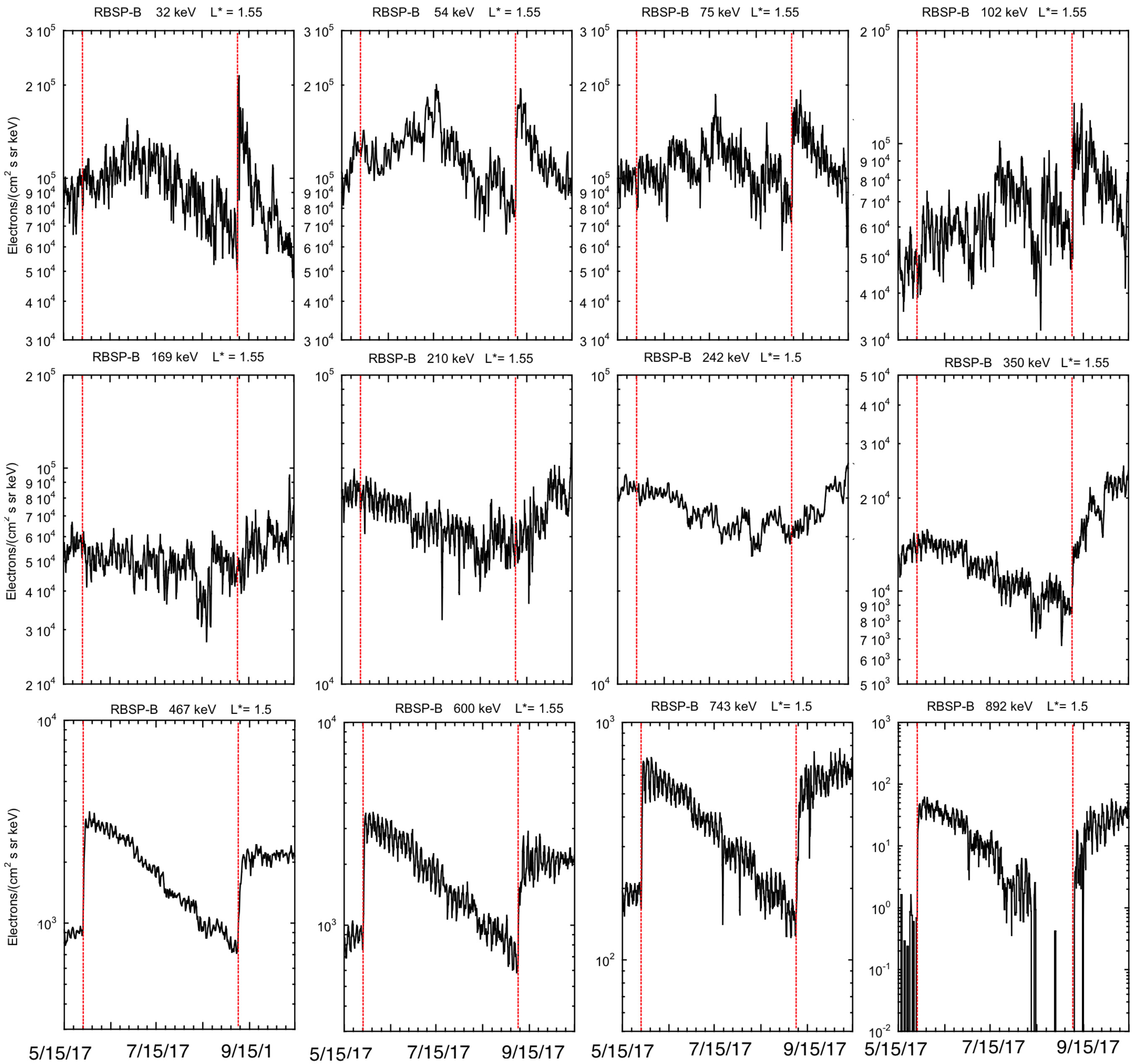


- Panel (c) for Mu~9.6, shows PSD increased for L*>2.3 and at L*=1.5 (the flux not removed by correction algorithm)
- Panel (d) with Mu=45.8 shows PSD increase over all L*≥2
- Panel (e) for Mu=130 shows PSD increased for L*≥3
  - *Note that the fluxes for Mu=45.8 and 130 were near or at background at the lowest L**



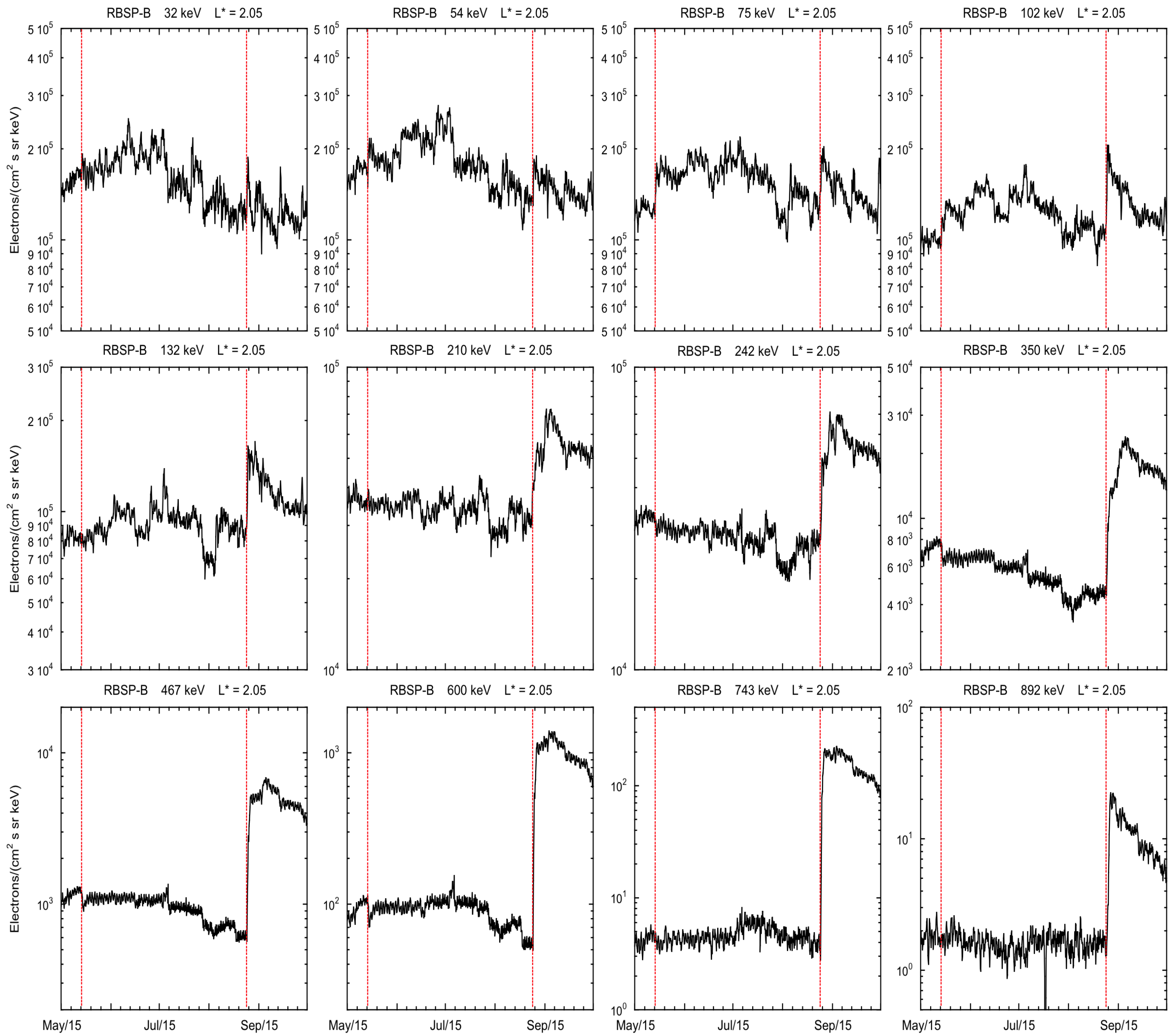
L*=1.55 Time Histories For May and Sept Storms

- Slices at L*=1.55 for 32-862 keV electrons for 15 May to 15 October 2017 (red lines show onsets)
- The 169 to 242 keV electron fluxes did not show an obvious response for either storm
- The ≤102 keV fluxes showed a response only for the September storm
- ≥467 keV electron fluxes responded strongly for both storms at L*=1.55
  - ≥740 keV fluxes were still rising a month later following Sept storm



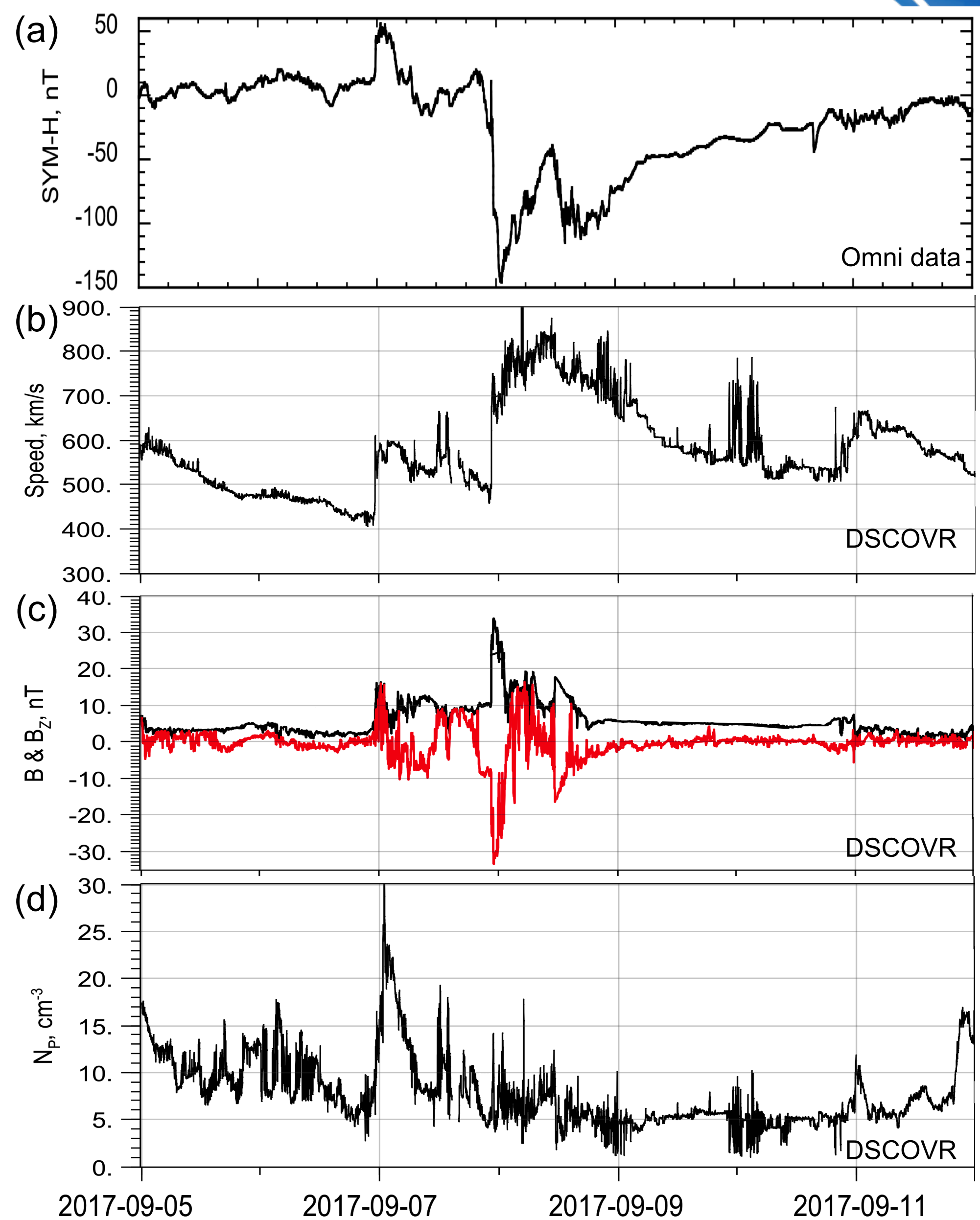
L*=2.05 Time Histories For May and Sept Storms

- Slices at L*=2.05 for 32-862 keV electrons for 15 May to 15 October 2017 (red lines show onsets)
- The flux responses varied from no, to small, and to large increases depending on the energy
- Small (factor of 1.5-2) variations occurred often for <240 keV at L*=2.05
  - Even in response to smaller storms



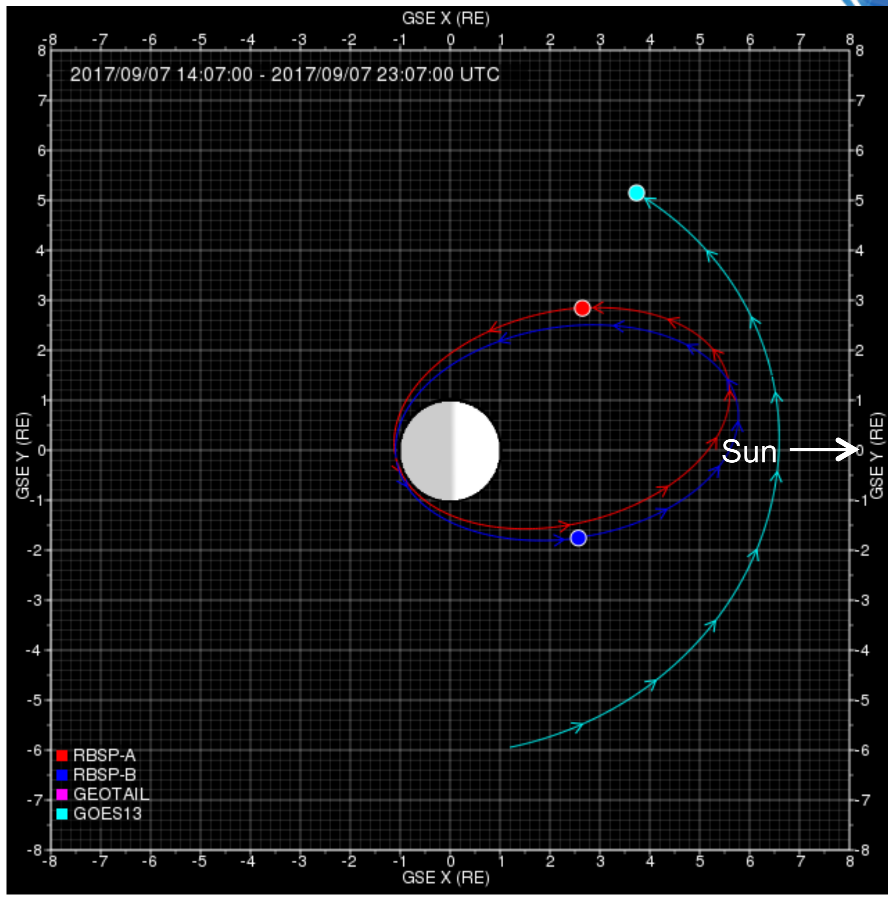
Conditions for the Sept. 7, 2017 storm event

- The storm started in response to a jump in the solar wind speed (c) and a strong southward turning of the interplanetary magnetic field (d) just prior to 00:00 UT on 8 Sep
- The major dynamic pressure pulse, occurred a few hours earlier (d) with a 200 km/s jump in the solar wind speed near 00:00 UT on 7 Sep, causing a disjoint SSC (a)
- SYM-H (a) started falling as Bz turned southward (c)
- The solar wind speed (b) reached high levels for this event



RBSP-A and RBSP-B Positions At Shock Arrival

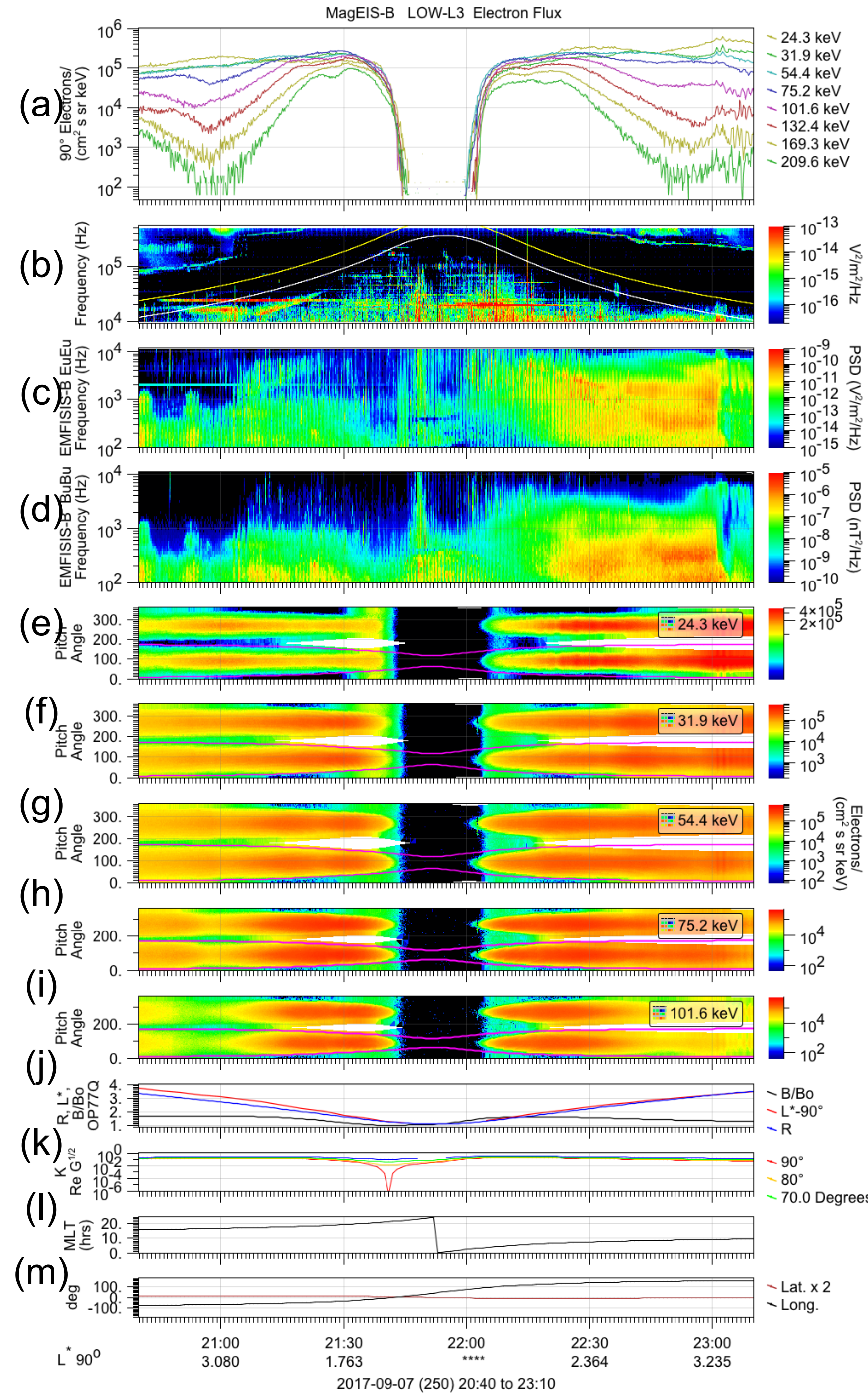
- The interplanetary shock passed through the magnetosphere at ~23:07 UT on 7 Sept. 2017
- The Van Allen Probes RBSP-A and RBSP-B were far apart in local time (and longitude) with RBSP-A inbound towards perigee and RBSP-B outbound from perigee but both on the dayside
- The energetic electron spectrometers on both satellites observed the electron response to the shock passage
- (Hudson and Kanekal)
- On following slides we show the electron responses at Low L* based on MagEIS Low and Medium energy data from RBSP-B
  - No comparable data from RBSP-A because of a commanding issue



RBSP-B Data During Storm Early Phase at 14:00-17:30 UT 7 Sept.

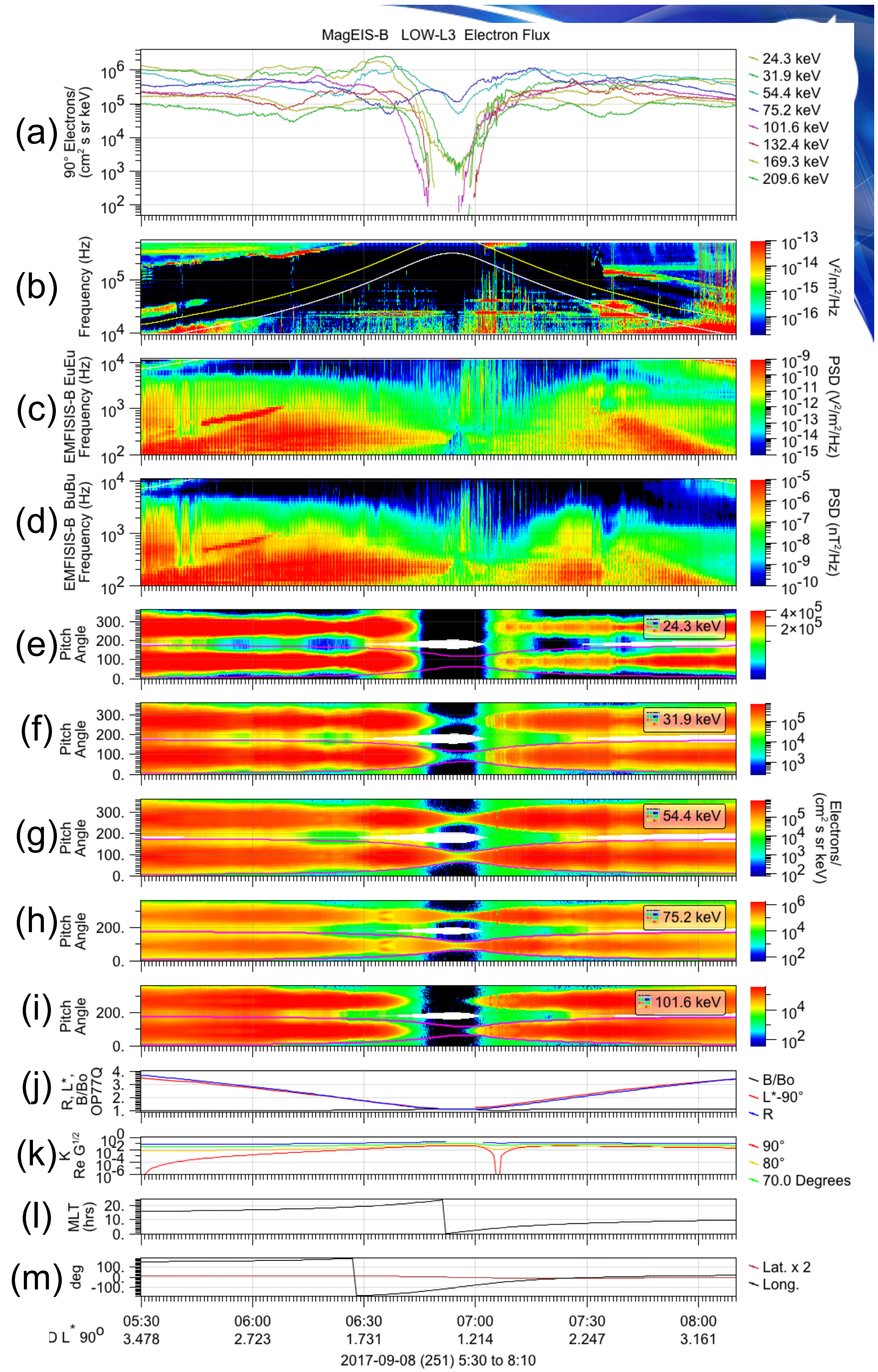
- MagEIS LOW and EMFISIS observations just prior to the arrival of the traveling IMF shock
- The panel arrangements are identical to those shown earlier for the May storm
- These panels show a pre storm reference data set with moderate wave activity and smooth electron flux profiles and pitch angle distributions

- For this storm period there weren't MagEIS data from RBSP-A because of a commanding issue



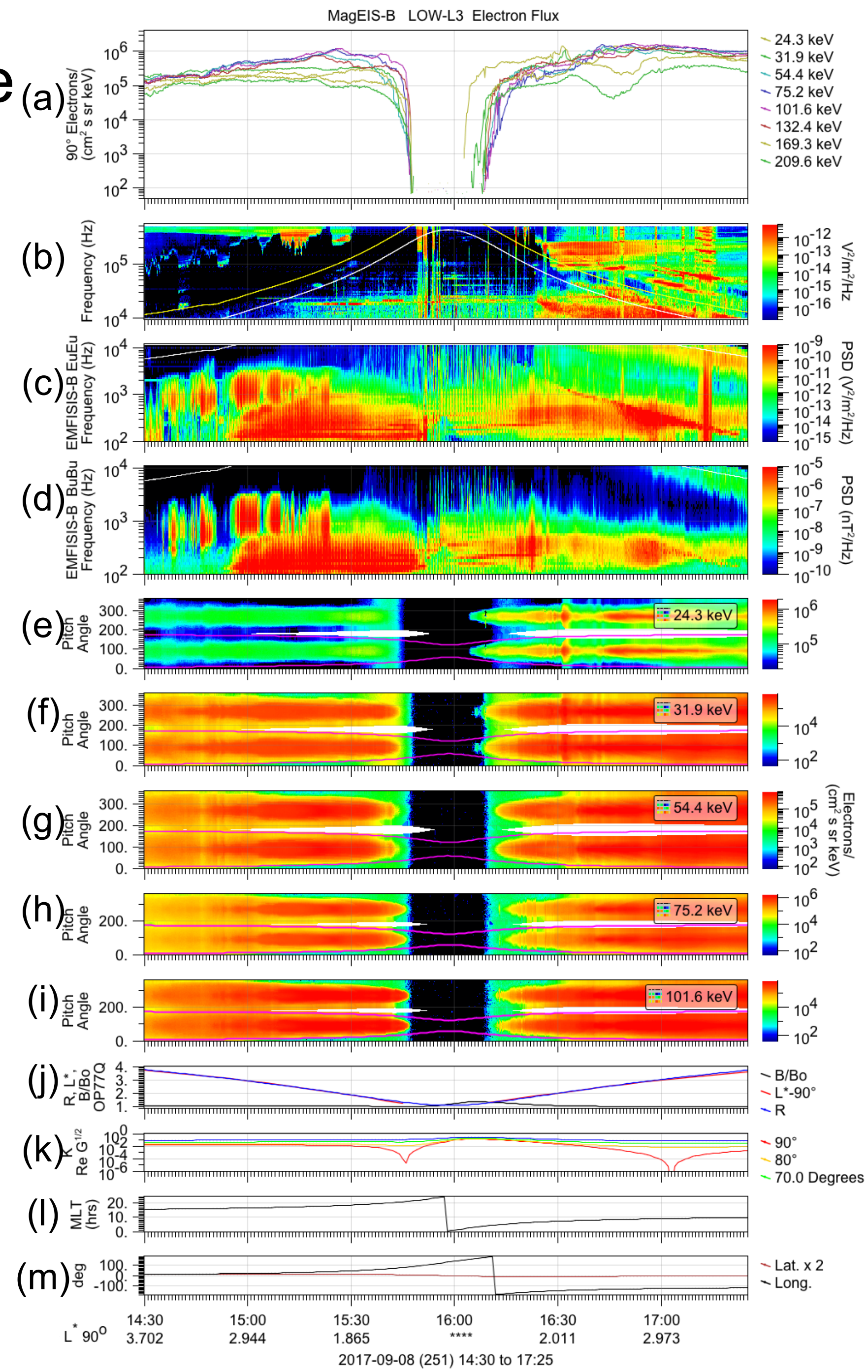
RBSP-B Data Early In Storm Main Phase on 8 Sept.

- Like during the May storm, the electron fluxes show structured profiles inbound and outbound from perigee, intense chorus-like wave activity to relatively low L* and structure in the electron pitch angle distributions
- Different from the May observations, some of the electron fluxes are raised throughout the perigee passage indicating the injected electrons had closed drift shells that were above the region of strong atmospheric losses as is shown in panels (a), (f)-(h)
- The structure changes in the electron pitch angle distributions near 07:40 UT appear to correspond to the presence of the strong wave emissions near fce/2



RBSP-B Data Later In Main Phase on 8 Sept.

- The storm had started into recovery but that was interrupted by a second drop in SYM-H (see earlier slide) causing a resurgence of low L* activity in both the electron fluxes and wave activity as is seen in the second half of the plot as RBSP-B is outbound from perigee
- Note the burst of pitch angle broadening in panels (e) and (f). These occur at the low L* end of the chorus-like emissions just after 16:30 UT
- There is even a small detached burst of ~32 keV electron flux at ~16:10. We do not know what caused that and it only occurred at that particular energy



L*=1.55 Time Histories For May and Sept Storms

- Slices at L*=1.55 for 32-862 keV electrons for 15 May to 15 October 2017 (red lines show onsets)
- The 169 to 242 keV electron fluxes did not show an obvious response for either storm
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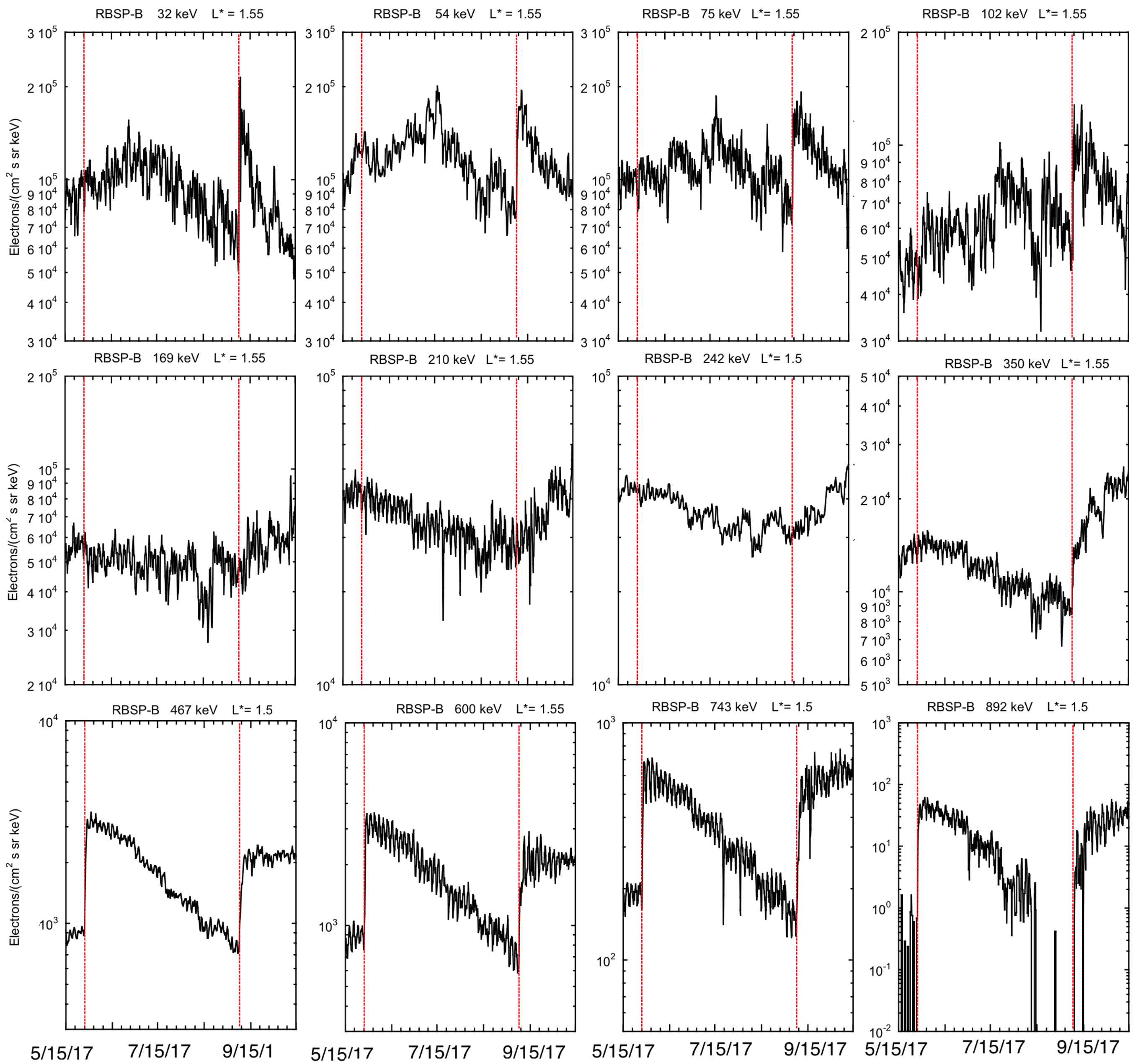
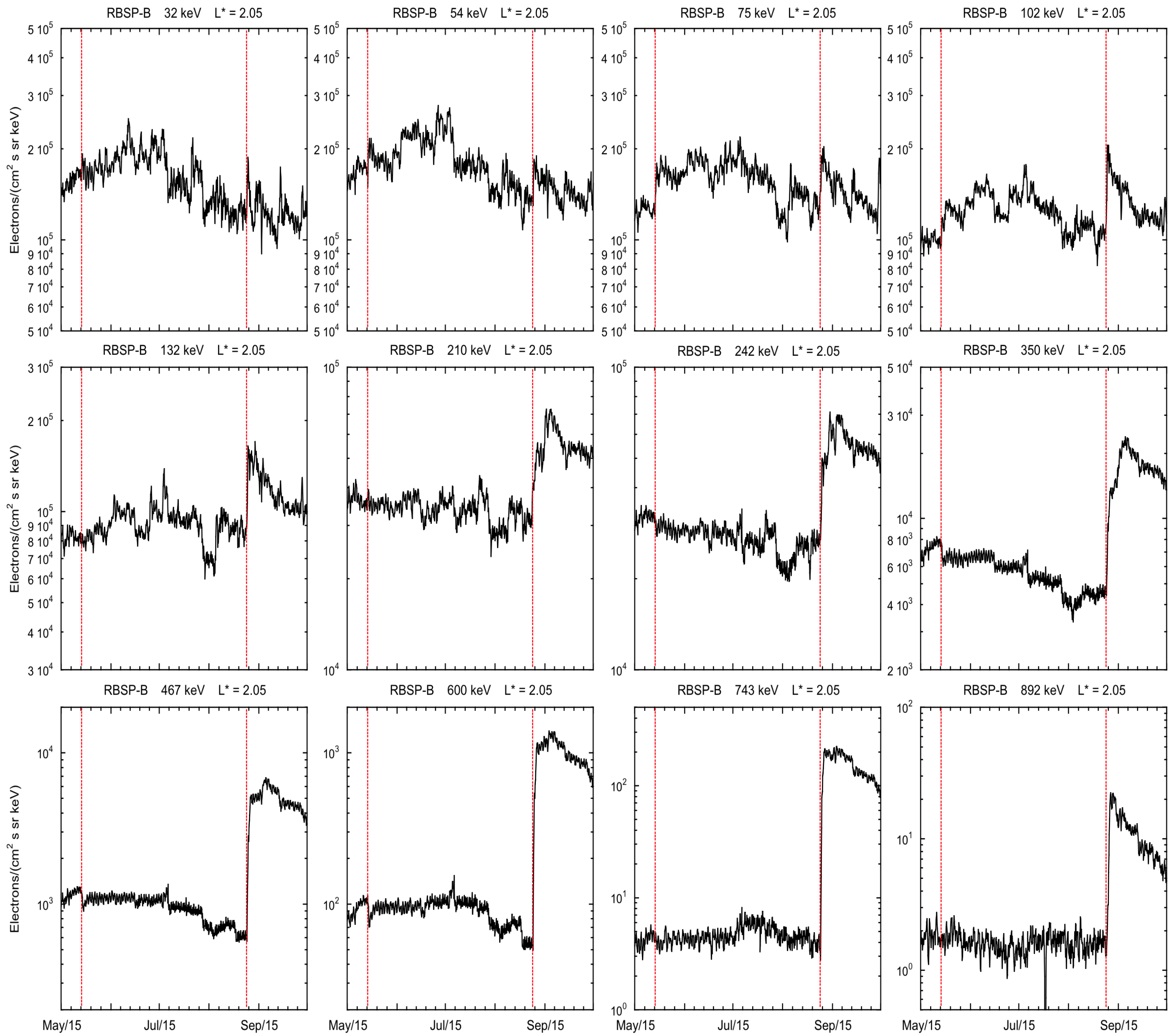


L*=2.05 Time Histories For May and Sept Storms

- Slices at L*=2.05 for 32-862 keV electrons for 15 May to 15 October 2017 (red lines show onsets)
- The flux responses varied from no, to small, and to large increases depending on the energy
- Small (factor of 1.5-2) variations occurred often for <240 keV at L*=2.05
  - Even in response to smaller storms



Summary

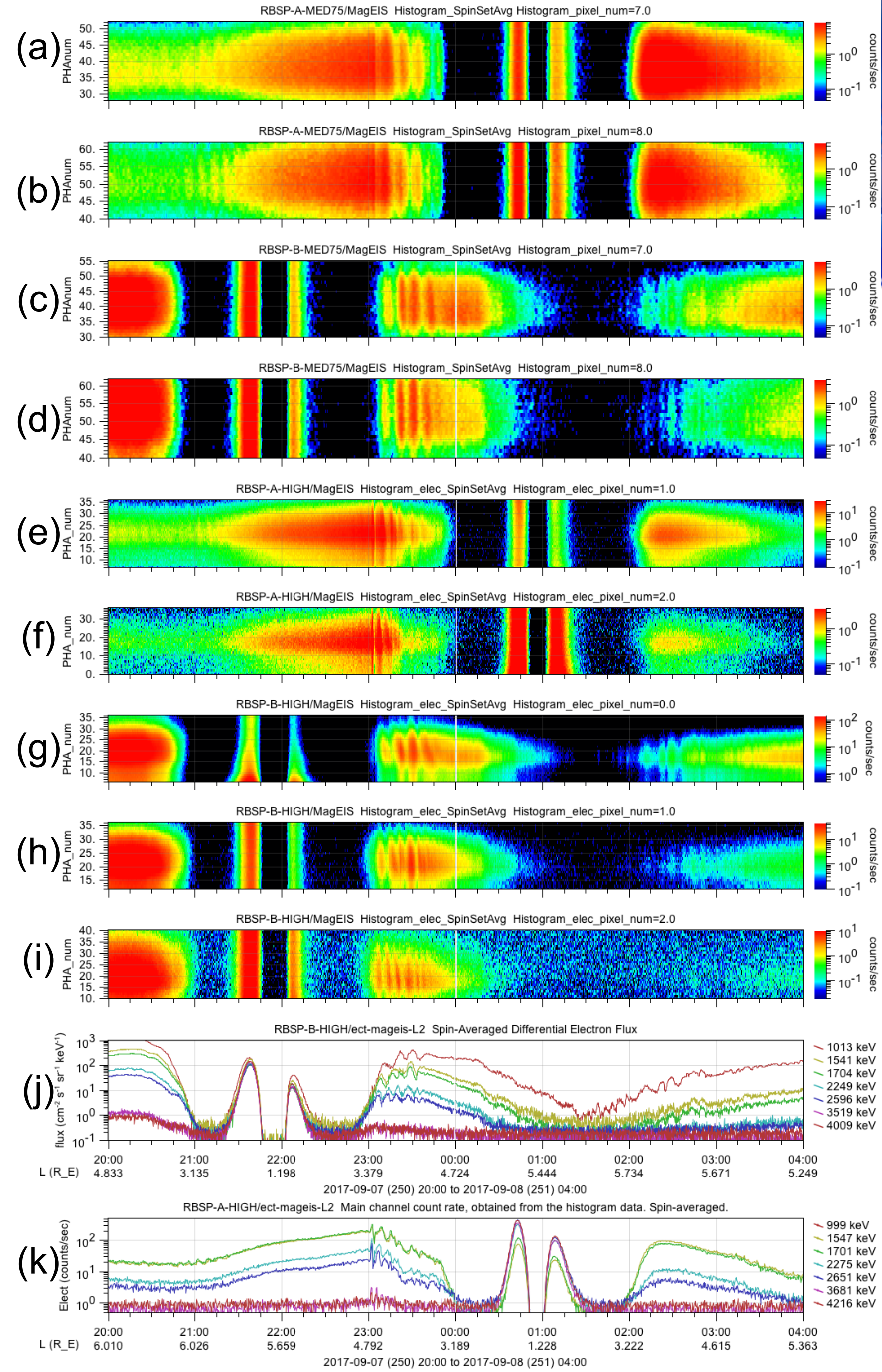
- Both the May and September storms showed similar features in the 25-200 keV electron fluxes at low L*
- The immediate response was increased but structured fluxes in these inner regions
- Electrons penetrated to low L* depending on their Mu with the larger Mu showing larger increases in phase space density at lowest L*
- As was shown in an early slide, the storms created new belts of 400 – 900 keV electrons below L* ~ 2 which lasted for many days after the May storm and for over a month after the September storm
- These results are similar to the low L* electron penetrations observed by Turner et al. (2015, 2016) that will be summarized by Turner in a following presentation
- Not all the features of the waves observed at low L* are understood, however it is clear from this study that they are associated with dramatic changes in the low energy electron angular distributions in the inner radiation zone that need further study
- Although there were traveling interplanetary shocks that traversed the magnetosphere associated with both storms, only the September shock caused a strong response in the energetic electrons and in that case only at >600 keV. (Kanekal et al. [paper 330259] discussed the September shock in greater detail yesterday)

THE END

Backup Slides

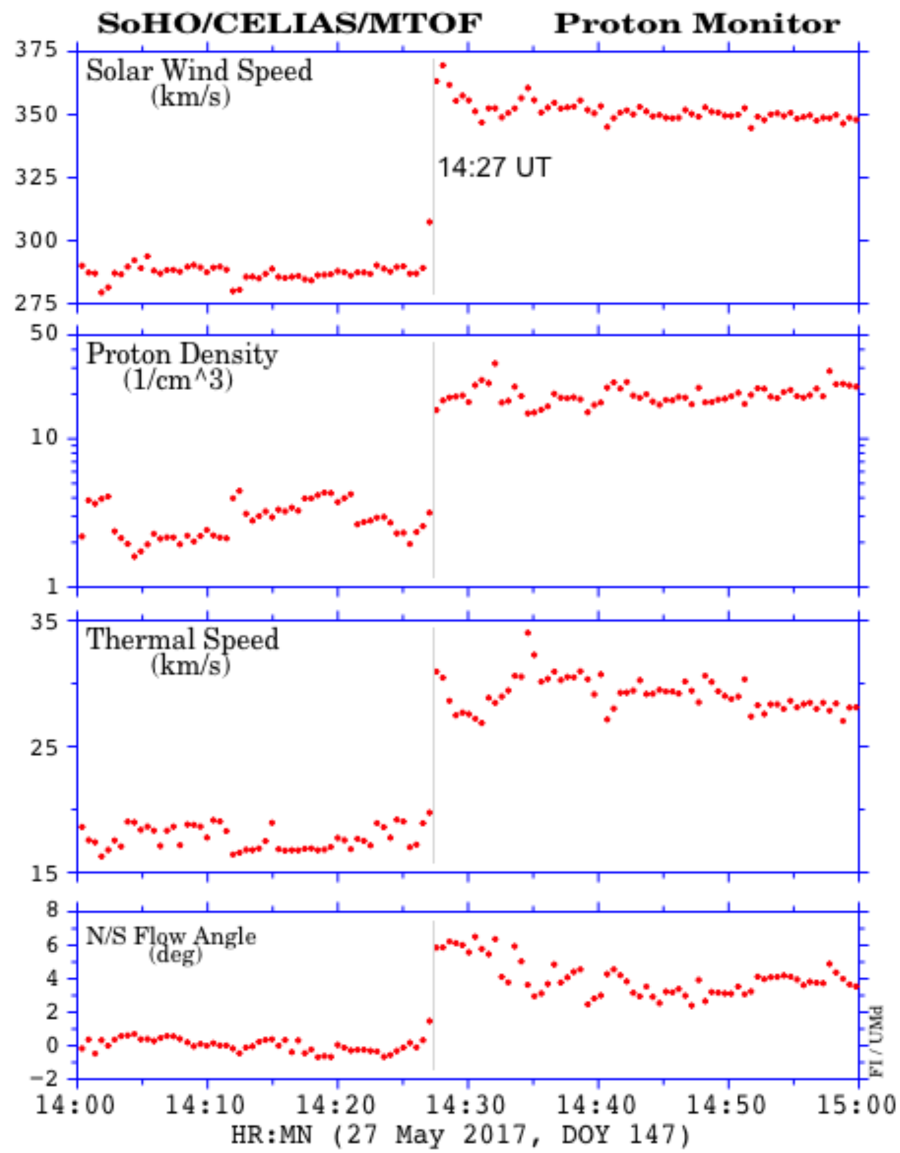
MagEIS Energetic Electron Response To Shock Passage on 7 Sept. 2017

- There are clear ringing flux signatures in the RBSP-A and RBSP-B high energy data starting near 23:00 UT on 7 Sept.
- Panels (a) and (b) show data from two MagEIS detectors on RBSP-A measuring electrons at ~900 and ~1100 keV respectively
- Panels (c) and (d) are for similar energies but on RBSP-B
- Panels (e) and (f) are for electrons with energies near 1000 and 1500 keV on RBSP-A
- Panels (g)-(i) are for electrons with energies near 1000, 1540, and 1700 keV on RBSP-B
- Panels (j) and (k) show line plots of the spin averaged fluxes from different detectors on RBSP-A and RBSP-B respectively
- As can been seen, the responses were nearly simultaneous at both satellites
- However, no response was observed at energies ≤600 keV indicating these electrons had drift periods that could not resonate with the shock's temporal passage



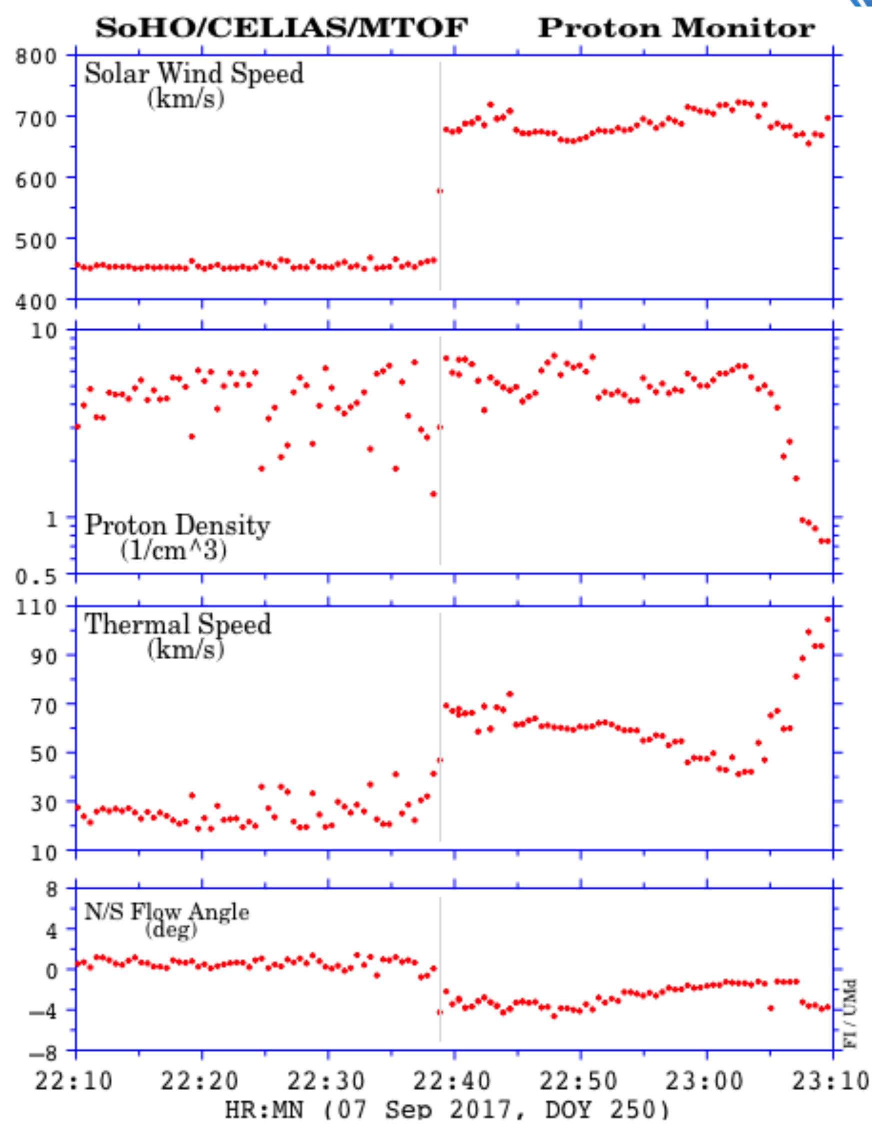
Interplanetary shock observed by SoHO/MTOF on 27 May

- The shock at SoHO occurred at 14:27 UT on May 27
- The solar wind speed was relatively low so the shock arrived at Earth more than an hour later near 15:45 UT
    - *There was an initial spike in the pressure at 15:41 UT*
- Van Allen Probe B was just rising from perigee in the post noon sector at this time while Probe A was descending towards perigee near 20 MLT
- As we will show later, both Probes observed a ULF response in the energetic electrons to the shock passage, essentially simultaneously



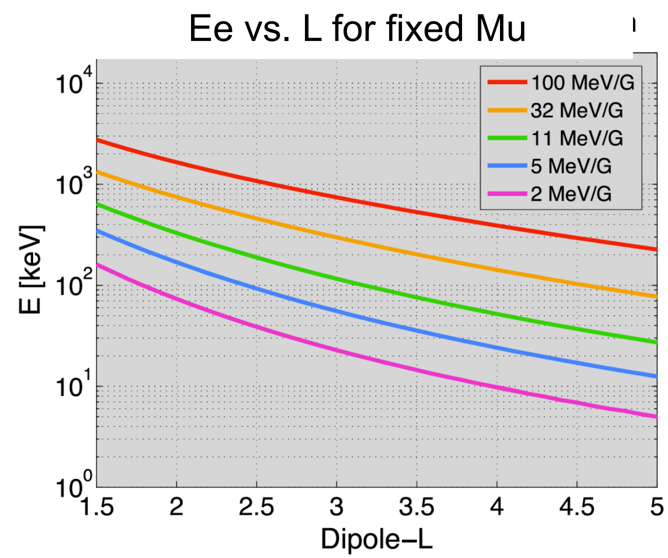
Interplanetary shock observed by SoHO/MTOF on 7 Sep

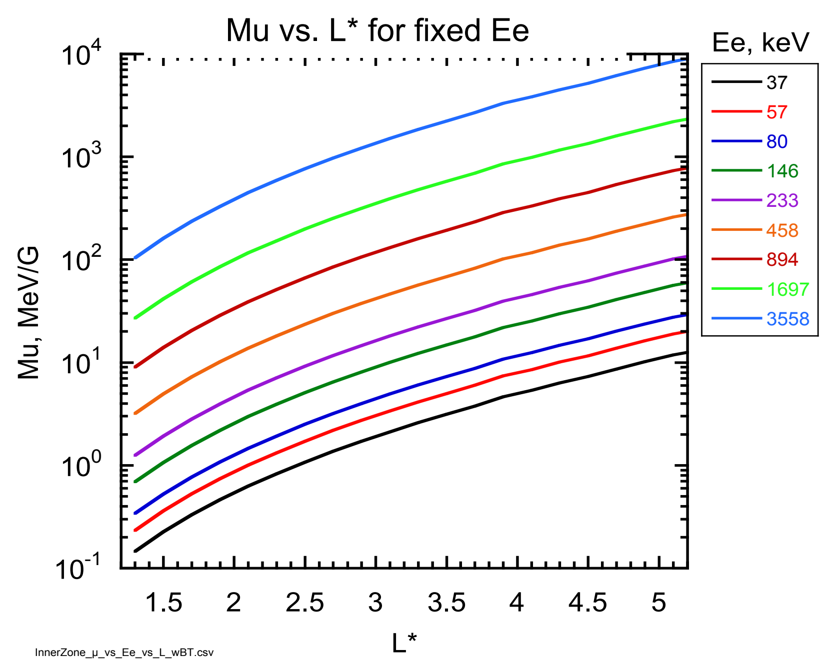
- The shock at SoHO occurred at 22:38 UT on 7 Sep
- The solar wind speed was high behind the shock that arrived at Earth near 00:00 UT on 8 Sep
  - *There was an earlier shock on 6 Sep near 23:13 UT associated with a jump in both the solar wind speed and the dynamic pressure*
- Van Allen Probe B was just rising from perigee in the post noon sector at this time while Probe A was descending towards perigee near 20 MLT
- Both Probes observed a ULF response in the energetic electrons to the shock passage, essentially simultaneously



Relationship Between Electron Energy, Mu and L

- Plot of electron energy versus L for a fixed first adiabatic invariant, Mu, (top panel) shows how an electron's energy is increased when transported from large L to small L while conserving Mu (and K, not shown)
- Similarly, the bottom panel shows how the Mu value changes with L* for a fixed electron energy
- If an electron is transported from the outer radiation zone (L=5) to the center of the inner radiation zone (L=1.5) its energy could increase by a factor of ~12 to 30 in the process if the first adiabatic invariant is conserved
- This is one explanation for how highly energetic electrons show up at low L during active periods
- A second explanation involves in situ acceleration by resonance with waves that violates the first invariant

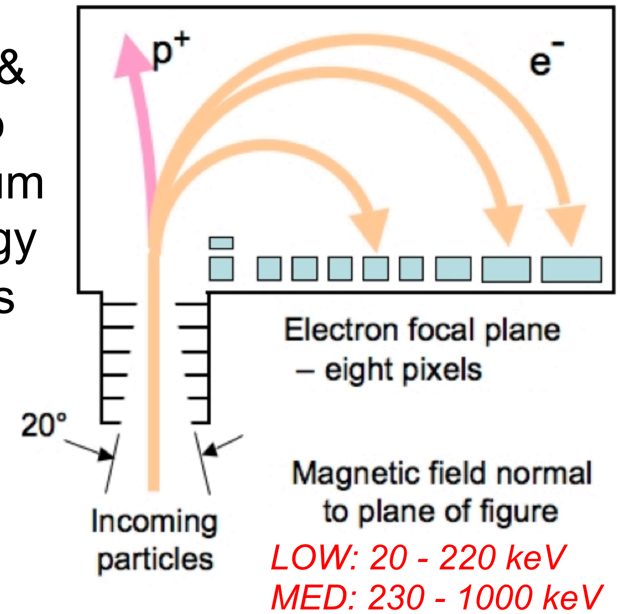




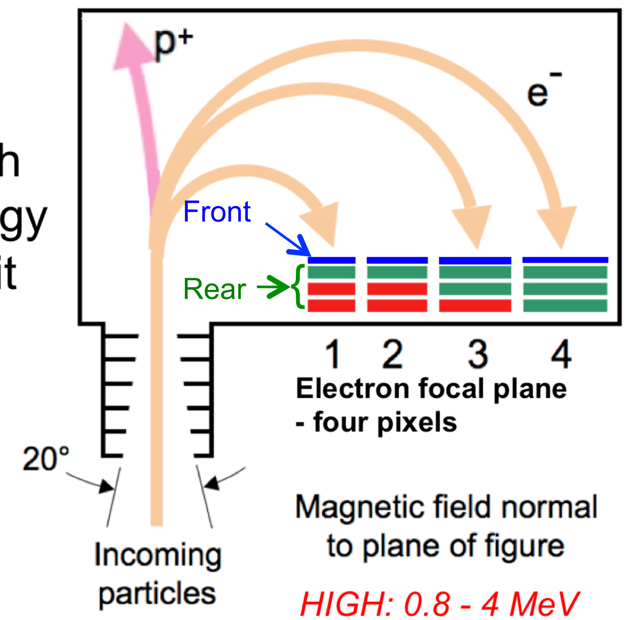
MagEIS Electron Sensors

- MagEIS uses magnetic spectrometers to measure electron fluxes
- The spectrometer’s magnetic field momentum analyzes the electrons focusing a limited energy range on each detector pixel
- The energy deposits are digitized by a 256 channel pulse-height analyzer
- Look-Up-Tables (LUTs) are used to extract only those energy deposits that are consistent with the momentum of the electron and the position of the detector pixel in the magnet’s focal plane
  - *This allows us to determine the background from the “wings” of the pulse-height distribution and subtract it out later*
- The high energy unit uses coincidence between its Front and Back detectors to further reduce the background response

Low & Two Medium Energy Units



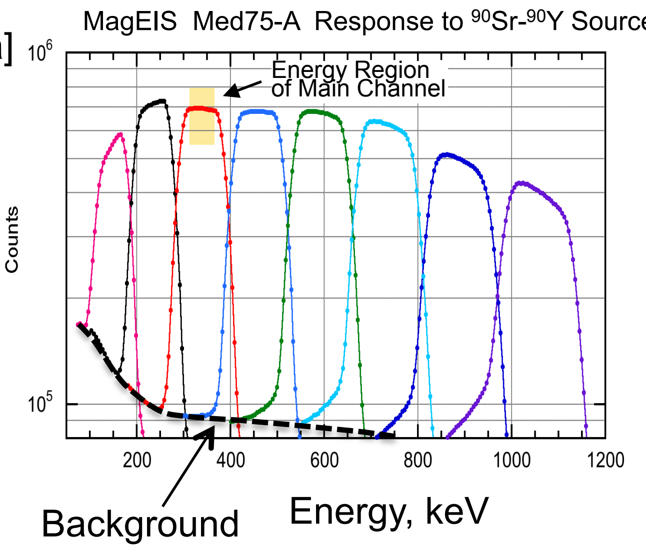
High Energy Unit



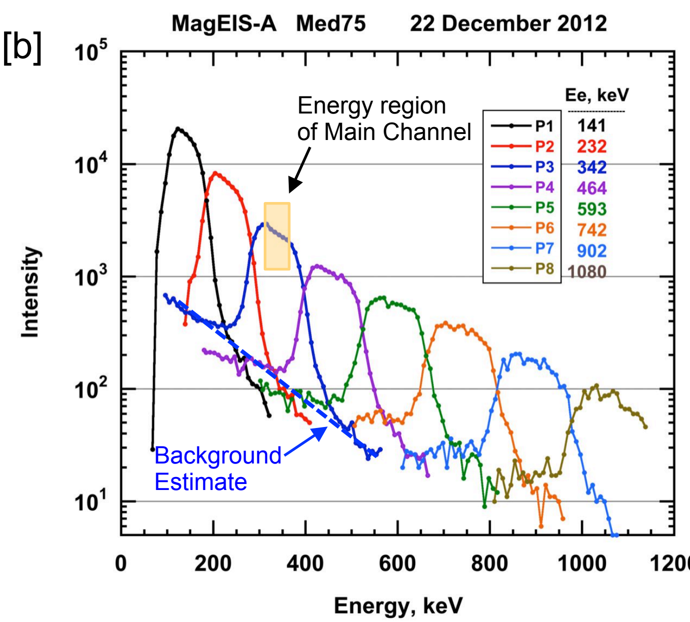
MagEIS Energy Channels and Histograms

- Plot [a] shows the response of the MagEIS-A Med75 spectrometer to a ^{90}Sr-^{90}Y beta source
  - *The source has a broad relatively flat beta spectrum covering the full energy range of the Med75 unit*
- The points indicate the individual pulse-height energy channels that define the response peaks
- The histogram data for this unit extends over a larger range of energies than shown here for each energy channel
- The main channels are taken from the “sweet spot” of each detector’s response as shown by the shading on the red curve.
- Plot [b] shows the steep electron spectrum observed by the same spectrometer in the radiation belts for L~4
  - *These are from the on-orbit histogram data*
  - *The center energy of each channel is indicated in the legend*
  - *Background was estimated from the “wings” of the histograms*

[a]



[b]



Abstract

Electron transport and penetration into the radiation belt slot region is fairly common for electrons with energies <1 MeV. However, the transport and penetration of electrons deep into the inner radiation zone, L*<2, is not common. We will show observations taken during a moderate magnetic storm (SYM-H -140 nT) on 28-29 May 2017 when the 20-200 keV electrons were observed to penetrate down to L*~1.5 following storm-time substorm injections. The electrons had highly structured flux versus L* profiles. At the same time chorus emissions were observed down to L*~1.7 in regions where the density, estimated from the upper hybrid resonance, was 800-1600 cm^{-3} indicating the chorus was inside the plasmasphere. Both Van Allen Probes observed the low L* electron penetration and the chorus emissions during perigee traversals with the satellites separated by about three hours. The traversals occurred very close to the magnetic equator. These events are similar to recent observations by Turner et al. 2015 and 2017.

Turner, D. L., et al. (2015), Energetic electron injections deep into the inner magnetosphere associated with substorm activity Geophys. Res. Lett., 42, 2079–2087, doi: 10.1002/2015GL063225.

Turner, D. L., et al. (2017), Investigating the source of near-relativistic and relativistic electrons in Earth's inner radiation belt, J. Geophys. Res. Space Physics, 122, 695–710, doi:10.1002/2016JA023600

Fennell, J. F., et al. (2014), Inner Radiation Zone and Slot Region Electron Fluxes: ECT/MagEIS Data, AEROSPACE REPORT TOR-2015-01548