Heliophysics Big Year
Solar Maximum

Janet Kozyra
Elizabeth MacDonald
NASA Heliophysics Division

HPAC Meeting 14-16 Nov 2023
HBY is not just citizen science nor eclipses – solar max has opportunities for innovation!
Seeking scientific collaborators, data, and people wranglers

ISS Nov 5 2023, https://x.com/phi48/status/1722248359313133705?s=20
International Geophysical Year (IGY) 1957-58
- Radiation Belts
- Sputnik, Explorer I
- Plate Tectonics
- Established NASA
- Nations working together

International Heliophysics Year (IHY) 2007-8
- 50-year Anniversary IGY
- Space Weather
- Scientific Cooperation
- Scientific Capacity Building

Heliophysics Big Year (HBY) 2023-24
- Citizen Science
- Solar Eclipses
- Sun-Geospace System Focus
- Approach to Solar Max
- Solar Superstorm Dynamics

- Parker Solar Probe: Touch the Sun
- Solar Dynamics Observatory: Big Data
- HSO expanded to 20 operating missions, 2 missions in development, 10 in formulation
- Citizen Science invaluable contributor to science discovery

Citizen Science in the Big Year
"Birds", take over for Solar Max
Implementation: Heliophysics Big Year, Solar Maximum

As was done in IGY and IHY, the goal is to come together and look for synergistic opportunities that present pathways to scientific advancement with immense potential.

HBY enables us to address ambitious research questions using complementary skills and resources, join efforts through open science across programs, science communities, individual researchers, and citizen scientists, each enriching the others, while actively focusing on inclusion, diversity, equity, & accessibility in ways that:

• Generate excitement
• Enable new discoveries
• Give us quick wins on the time scale of the HBY
• Create legacy associations that will live on after HBY
• Enable innovative, comprehensive analysis of dangerous solar storms

1. Recruit internal NASA and external working groups to:
   Develop overall strategy and plans for the first workshop in early 2024 and future interactions

2. Launch “HBY Solar Max” workshop with 3 elements
   • Pilot studies of two major storms that occurred in March and April of 2023 (and possibly another in November 2023) associated with red aurora at low latitudes, and other unusual phenomena, with great potential for giving insights into superstorm dynamics.
   • Joint session with citizen scientists to integrate their data & inputs of science questions
   • Brain-storming sessions to collect input on needed infrastructure based on the pilot studies

3. Seek out mutually beneficial synergies between programs, including:

<table>
<thead>
<tr>
<th>Year of Open Science</th>
<th>ISWAT</th>
<th>AWS</th>
<th>ISTPNext</th>
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<tbody>
<tr>
<td>SMD Citizen Science</td>
<td>HSO missions</td>
<td>Google</td>
<td>More!</td>
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<tr>
<td>IDEA group</td>
<td>DRIVE Science Centers</td>
<td>CCMC/GSFC</td>
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4. Prioritize IDEA (inclusion, diversity, equity, accessibility) & public outreach
   • Ensure that the external advisory group members span diversity elements to guide campaigns and develop plans for infrastructure. Accessibility will be a key consideration.
   • Participate in interactions with the public that increase their level of engagement and enhance understanding of space weather, space climate, and societal impacts

5. Optimize existing tools & develop others (when possible)
   • Internal and external communications,
   • System-level data products for HSO
   • Algorithms to stitch together auroral images
   • More!
The Helio Big Year is here

Eclipse projects
For more info, check out overview posts on citizen science from @NASASun and the Aurorasaurus blog.
December’s Helio Big Year theme is citizen science!

**ROSES Opportunities**
- **H-CSI (3 year) Citizen Science Investigations**
  - Step 1 Nov 15 2023
  - Step 2 Jan 26 2024
- **Seed funding CSSFP (1 year)**
  - NOI (optional!) Nov 21 2023
  - Proposals due Jan 24 2024

**Points of contact:** Ha-Hoa Hamano, Liz MacDonald
hq-heliobigyear@mail.nasa.gov

Stay updated with everything HBY. Subscribe to our new community [mailing list](mailto:mail.nasa.gov).

Join in on the fun and create a zine or spotting guide with this [template](mailto:template).

**New Helio Big Year poster** connecting readers to projects and resources

Preview our participatory HBY Zine activity guide. Look out for a zine digital library debut/use cases.
THEMES: Solar Cycle 25
Approach to Solar Maximum 25
Will solar cycle maximum be more intense than predicted? Arrive sooner?

**Solar Cycle progression - Sunspot number**

- July 2012, Carrington-level event just missed Earth
- April 2024 Solar Max or July 2025 Solar Max
- Feb 2022 Loss 38 Starlink Satellites
- Apr 2024 Solar Max
- July 2025 Solar Max

**2 Superstorms**
- 23-24 March 2023 (-170 nT)
- 23-24 April 2023 (-178, -233)

Both: Erupting filaments

![Graph showing the progression of sunspot numbers with markers for solar maximum and superstorms.](https://www.spaceweatherlive.com/en/solar-activity/solar-cycle.html)
Event Studies of Dangerous Superstorms
Interesting & Unusual Storm Features
<table>
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<tr>
<th>Compelling Issues for HBY Solar Max Storms</th>
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<tbody>
<tr>
<td><strong>23-25 March 2023 Solar Storm</strong></td>
<td><strong>23-25 April 2023 Solar Storm</strong></td>
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<tr>
<td>Filament eruption (large uncertainty) – stealth CME</td>
<td>Filament eruption</td>
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<tr>
<td>Vicinity of a recurrent coronal hole</td>
<td>Vicinity of the same recurrent coronal hole next CR</td>
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<tr>
<td>ICME &amp; storm profile remarkably similar to Apr 2023</td>
<td>ICME &amp; storm profile remarkably similar to Mar 2023, 31 days apart</td>
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<tr>
<td>BSN (bow shock normal in Omnidata) reached 12-16 RE in the recovery phase of the storm</td>
<td>BSN (bow shock normal in Omnidata) expanded to &gt;30 RE (?) in the recovery phase of the storm</td>
</tr>
<tr>
<td>Red aurora observed in California, New Mexico, North Carolina, Florida (Characteristic of superstorms)</td>
<td>Red aurora observed in California, New Mexico, North Carolina, Florida (Characteristic of superstorms), UK</td>
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<tr>
<td><strong>Visible SAR Arc, STEVE</strong></td>
<td><strong>Visible SAR Arc, STEVE, proton auroral spots</strong></td>
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<td>Exceeded 1 TW in the upper atmosphere - the 7th strongest storm observed by SABER over past 21.5 yrs</td>
<td>Exceeded 1 TW in the upper atmosphere - the 8th strongest storm observed by SABER over past 21.5 yrs</td>
</tr>
<tr>
<td><strong>Plasma bubbles and EIA crests</strong> at unusually high latitudes (~36° N). <strong>Strong PPEF</strong> observed. Superfountain?</td>
<td><strong>Activity in auroral oval</strong> abruptly disappears in the storm recovery phase</td>
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</table>
Odd Similarities (?)  What does it imply?

23-25 March 2023 (min SYM-H = -170 nT)

23-25 April 2023 (min SYM-H = -233 nT)

Approximate timing:
- ~06:30 UT: Start of storm
- ~02:30-05:30 UT: Storm peak
- ~08:30 UT: Start of storm
- ~03:00 – 06:00 UT: Storm peak

- Red aurora in Flagstaff, AZ, 3:54-5:12 UTC
- Proton aurora EIA at >30° MLAT
- Expanded magnetopause, less radiation belt loss, high fluxes?
Observations of 23-24 Mar and 23-24 Apr 2023 Storms
Suspected Erupting filament on 20 Mar 2023

Courtesy CCMC DONKI: A faint, wide CME seen to the southwest in SOHO LASCO C2 imagery during a STEREO A data gap and occurring during a subsequent campaign with limited imagery. Associated with a broad area of coronal restructuring, coronal dimming, destabilization, and filament eruptions seen in SDO 193 and 304 starting around 2023-03-20T01:53Z bounded by an area created by S10 to S30, W05 to W30.

Submitted on 2023-03-20T13:08Z by Chris Stubenrauch
https://kauai.ccmc.gsfc.nasa.gov/DONKI/view/CME/24313/1
Erupting filament on 21 Apr 2023 associated with M1 Flare
Recurrent coronal hole
Strong NW IMF

SSUSI, DMSP F17
https://ssusi.jhuapl.edu/gal_AUR
24 March and 24 April 2023 storms: 7th and 8th largest amount of thermal energy in the upper atmosphere in 21.5 years of storms

Thermosphere Climate Index (TCI) tells how much heat (Watts) nitrogen oxide (NO) molecules in the thermosphere are radiating into space absorbed from solar flares and geomagnetic storms. 24 March and 24 April 2023 storms have the 7th and 8th largest TCI numbers observed by TIMED/SABER over the past 21.5 years, at 1.04 TW and 1.02 TW, respectively.

23-25 April 2023
GOLD 135.6 nm image
23 April 2023, 21:10 UT

Figure: The bright regions show the equatorial ionization anomalies (EIA) which are far poleward of their normal location, which is ± 15° MLAT. Indicates strong prompt penetration electric fields. The dark lines running through the EIA are low-density plasma bubbles that have been shown to be responsible for communication disruptions at mid-latitudes. Courtesy: Richard Eastes

Above: NASA’s daily Thermosphere Climate Index tracks thermal energy in Earth’s upper atmosphere. So far, Solar Cycle 25 is far ahead of Solar Cycle 24. Credit: Linda Hunt
https://spaceweather.com/, Jun 2 2023
Folding in Superstorm Anomaly Detection Results
More details in the "Extra Slides" at the end of the file
How Does Anomaly Detection Fit In?

**AWS-NASA engagement** = Set of 4 use cases, carried out as part of the HPD participation in the Strategic Data Management Working Group activities.....

**Purpose:** “to explore and report on data management options that:

1. improve discovery and access for all SMD data,
2. inform future science data system capabilities needed to enable:
   a. tighter coupling between theory programs and NASA observations as well as
   b. greater scientific discovery by science data users, including those involved in cross-disciplinary/division investigations and citizen scientists.”

**AWS – NASA Superstorm Use Case Underlying Principle**

Fair to moderate space weather makes up the vast majority of observations and provides a baseline against which to identify superstorms (anomalies)

Physical processes must produce both:
- Typical range of conditions
- Rare extreme events

Changes in dynamics are marked by:
- Emergent phenomena
- Significantly modified features

Basis for using anomaly detection:
- Identifying changes in dynamics through emergent or anomalous features
Ion precipitation reaches lower latitudes than Electron precipitation during superstoms

19 channels, of ions and electrons per second (millions / day)

Each orbit becomes one time step

- Need ML-ready data
  - Impractical to use full data stream
  - Remove detector anomalies and nuisance signals—median filtering
  - Careful data reduction (averaging/filtering) to preserve signals of interest

Ion precipitation reaches as far south as red aurora observations (red dots)
Bottom Line: Why are soft ions in excluded regions? What determines deepest MLAT?

- PPEF is responsible for not only bringing the ions into midlatitudes but for stripping away the outer plasmasphere.
- Soft ions are able to penetrate to unusually low-latitudes.
- The equatorward transport is halted as these ions enter the plasmasphere and are depleted by Coulomb collisions.
The Geospace AD algorithm identifies (to our knowledge for the first time) a drop in the average energy of auroral electrons during the main phase as a characteristic feature of superstorms. Studies carried out for only a few cases [Sivjee and Shen, 1997; Steele et al., 1998; Hecht et al., 2008]

- How the decrease in average energy is related to storm severity and other storm processes requires further study.

This drop in energy had consequences for storm dynamics because lower energy than normal field-aligned current carriers resulted in closure currents at higher altitudes, and unusual conductance profiles. Changes coupling [c.f., Huang and Burke, 2004]
Drawing in Researchers & Citizen Scientists to Explore Sun-Geospace with Compelling Questions & Innovative Approaches
Compelling questions can be designed to engage all Helio discipline areas & Citizen Scientists

<table>
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<tr>
<th>Discipline</th>
<th>Potential Compelling Campaign Focus Areas</th>
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<tbody>
<tr>
<td>System</td>
<td>Are these superstorms? Is a superstorm just a larger version of a storm or have dynamics changed? Are these 2 storm events superstorms? Proto-superstorms?</td>
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<tr>
<td>Solar</td>
<td>What is source of the stealth CME driving the 23 Mar 2023 storm?</td>
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<td>Helio</td>
<td>Is it significant that (1) the filaments erupted 31 days apart, (2) near the same recurrent coronal hole, (3) the storms started within hours UT of each other upon arrival at Earth and peaked in the same 3-6 UT interval on the 2nd day.</td>
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<td>Helio</td>
<td>What links the coronal hole and filament eruption? Does the process persist and recur during the next CR? If so can this increase the predictability of superstorms?</td>
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<td>Helio/Mag</td>
<td>Are planar magnetic structures (PMS) a factor in the enhanced geoeffectiveness of the ICME during 23-24 April 2023 storm [Ghag, et al., 2023]</td>
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<tr>
<td>Mag</td>
<td>In these events, what disrupts ring current shielding of mid/low-latitude regions? How do resulting long-duration PPEFs create superstorm-like dynamics?</td>
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<tr>
<td>ITM/MAG</td>
<td>Are the Equatorial Anomalies and bubbles interacting with the plasmasphere? With storm enhanced densities?</td>
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<tr>
<td>ITM</td>
<td>What is pumping large amounts of heat into the upper atmosphere?</td>
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<tr>
<td>Citizen Science</td>
<td>When &amp; where do unusual auroral forms appear? How is that related to size and phase of the storm?</td>
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Extra slides
### Strategy: Heliophysics

#### Vision
- Leverage the HBY to develop a lasting structure that supports worldwide collaboration in the analysis of dangerous solar storms.

#### Mission
- Carry out pilots that explore what is needed to support: (1) seamless use of the HSO as a system-level observatory, (2) collaborative workspaces for open science, (3) data commons areas that are easily accessible for researchers, citizen scientists, and the public.

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<th>1. Seek New Understanding of Dangerous Solar Storms</th>
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<td>Use event campaigns as a powerful tool to focus multidisciplinary researchers on questions of mutual interest in how dangerous magnetic storms develop from sun to geospace &amp; their consequences.</td>
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<th>2. Integrate Citizen Science as a Critical Element</th>
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<td>Incorporate Citizen Science for key information on storms not attainable in other ways.</td>
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<th>3. Adopt Principles of Open Science</th>
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<td>Build on examples of worldwide collaboration during IGY1957-58 and IHY 2007-8 to create an open science environment that spurs innovation and new insights.</td>
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<th>4. Prioritize IDEA (inclusion, diversity, equity, accessibility)</th>
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<td>Identify synergies and areas for cross-collaboration, strengthen and forge relationships with underrepresented communities, innovate outreach activities with IDEA as a major focus.</td>
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<th>5. Optimize Existing Tools &amp; Develop Others</th>
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<td>Including internal and external communications, HSO as a system observatory, public engagement, campaign structure with an accessible data commons for observations &amp; models, open spaces for collaborative analysis, synergies between space-based &amp; ground-based observations, etc.</td>
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<th>6. Recruit Partners</th>
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<td>Foster mutually beneficial engagement with partners &amp; stakeholders including agency (i.e., GSFC, Langley), interagency (NSF, NOAA, DoD, etc.), international (i.e., ESA, ISTPNext, ISWAT), commercial (i.e. cloud providers), educational (i.e., science centers, universities) partners, &amp; the public.</td>
</tr>
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</table>
ISTPNext – priority to provide as soon as possible campaign data

HBY Journal Issue – Available to public

Note:
- Include citizen science as crucial element of global observations
- 1st *global continuous* observations of auroral storm (no time gaps, high resolution)
- 1st ever global view of *great red aurora*

ISTPNext Team with Sun-Earth Expertise

Initial Interpretation of Event

Platform for Collaborative Post Event Analysis (TOPS)

Extreme Space Weather Events 2023-24 - analogous to BAMS most downloaded issue.

Near Real-Time Observations

App & Internet

Full Data Set

Data Access Platform

Helio Researchers

Citizen Scientists, Non-Helio Researchers, Public

HSO Fleet

ISS Astronauts

Ground-based Facilities

Fleet

HBY Data Commons

Stitched together global auroral images

Data Subset in AWS “Registry of Open Data” ??

ISTPNext ISWAT

CCMC: ISWA, DONKI

Note:
- Tech developed for “Image Stitching” has use for Rocket-Launch Notilucent Clouds
- HBY Event Campaign structure may serve as a pilot for ISTP Next
- Leverages already engaged international ISTP Next community into HBY

FOCUS on storm event studies:

Storm Warnings

App & Internet

*multiple languages*

HSO & Int’l fleet

Ground-based Facilities

Citizen Science Inputs

STITCHED TOGETHER GLOBAL AURORAL IMAGES

Platform for Collaborative Post Event Analysis (TOPS)
1) Long-duration prompt penetration electric fields [Maruyama et al., 2007] result from:
   • Extreme magnetotail stretching due to rapid and continuous reconnection
   • Creates induction electric fields
   • Prevent the ring current from drifting inward to fully shield the convection E field

2) When the shielding breaks down the dynamics of the storm changes

3) Strong PPEFs can drive extreme erosion of the plasmasphere [Obana et al., 2019].
   • For example, plasmapause at 35° ILAT or L~1.5 in some longitudes during 29-31 Oct 2003 superstorm [Baker et al., 2004]

4) Particle tracing indicates that strong variable PPEFs are able to bring soft (< 1 keV) ions dawnward and to unusually low latitudes (at times <33° IL) during superstorms [Huang et al., 2006]

5) These ions are an additional energy source for SAR-arcs, pushing them into visible range

Use Anomaly Detection to determine which storms have low-latitude soft ions and what determines how far they penetrate.
Emergent features in superstorms

- DMSP F13 particle precipitation data
  - Bring to science-quality
  - Make ML-ready
- Feature Engineering
  - <1 keV ions
  - >1 keV auroral electrons
  - Average energy of auroral electrons
- Unsupervised Learning because of rarity of superstorms, not enough training data

The DMSP particle data accepted into the AWS registry of open data (at https://registry.opendata.aws/dmspssj/)
Great red aurora in February 10-11 1958 superstorm at low latitudes

Change in underlying dynamics?

Anomalous features of storms

Most common auroral emission is green & at high latitudes

Low latitude red aurora in superstorms during SC 23

Great Aurora Visibility

NOAA Space Weather Prediction Center, Boulder CO
Soft ions heat the electrons & increase electron temperatures, intensifying the SAR-arcs.

- Specifically look at hard electrons and soft ions.
Example of Anomaly Detection Results

- Trained RCF model using 2000-2002 DMSP data
  - Input includes soft ion flux (red), hard electron flux (green/blue) and average electron energy (bottom plot)
  - Included time-lags (past 3 orbits)
- Model outputs continuous anomaly score value for every data point
  - Set threshold of 3std above mean as “anomaly”

SYM-H & MA/MS was not used in the anomaly detection

SYM-H only plotted with results for a comparison to the previous standard for superstorms
What determines how far equatorward soft ions penetrate? Soft ions during most superstorms penetrate as deeply equatorward as 25° - 35°).

*Some superstorms shaded blue remained > 45°

### Table 2. Geomagnetic Storms in Which Warm Ions Reached the Lowest MLATs

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<tr>
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What determines how far equatorward soft ions penetrate? Not only a function of storm size.

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<tr>
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<td>-280</td>
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<td>9/11/05</td>
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<tr>
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<td>-220</td>
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<td>12/15/06</td>
<td>-210</td>
<td>45</td>
</tr>
<tr>
<td>11/06/01</td>
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<td>35</td>
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</table>

**Table 2:**

- **MLAT/LAT**: Magnetic local time at which the ions reached the lowest latitude.
- **L**: Magnetic latitude.

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<th>MLAT/LAT</th>
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<th>MLAT/LAT</th>
<th>L</th>
<th>MLAT/LAT</th>
<th>L</th>
<th>MLAT/LAT</th>
<th>L</th>
</tr>
</thead>
<tbody>
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<td>1.22</td>
<td>30°</td>
<td>1.33</td>
<td>35°</td>
<td>1.5</td>
<td>40°</td>
<td>1.7</td>
</tr>
<tr>
<td>45°</td>
<td>2.0</td>
<td>50°</td>
<td>2.4</td>
<td>55°</td>
<td>3.0</td>
<td>60°</td>
<td>4.0</td>
</tr>
</tbody>
</table>
What are the changes in dynamics associated with Superstorms?

(2) Why are soft ions in excluded regions?

(3) How are SAR-arcs and Great Red Auroras related?

(4) Is there a drop, rather than increase, in average energy of auroral electrons during superstorm peak?

Bottom Line: How are SAR-arcs & Great Red Auroras related?

- SAR-arcs reach high intensities in association with the peak region of soft ions (red).
- Separated from the equatorward edge of the auroral oval (green) by as much as 20° ILAT.
- The Great Red Aurora is associated with the equatorward edge of the auroral oval.
- This raises the possibility that SAR-arcs formed the low-latitude boundary of great red auroras extending them into view of the lowest latitude observers in the historical records.
How are SAR-arcs & Great Red Auroras (GRAs) related?

The location at which the soft ions terminate their equatorward motion is the location of maximum heating of the thermal electrons by the soft ions due to Coulomb collisions.

It is where the additional enhancement in the electron temperature occurs.

If large enough, this additional temperature increase pushes the SAR-arcs into the visible range.

Soft electrons at the equatorward edge of the auroral oval form GRAs.