Magnetospheric Seminar Series

August 2020

STEVE – a subauroral phenomena and the ultimate MI Coupling Challenge

Dr. Liz MacDonald

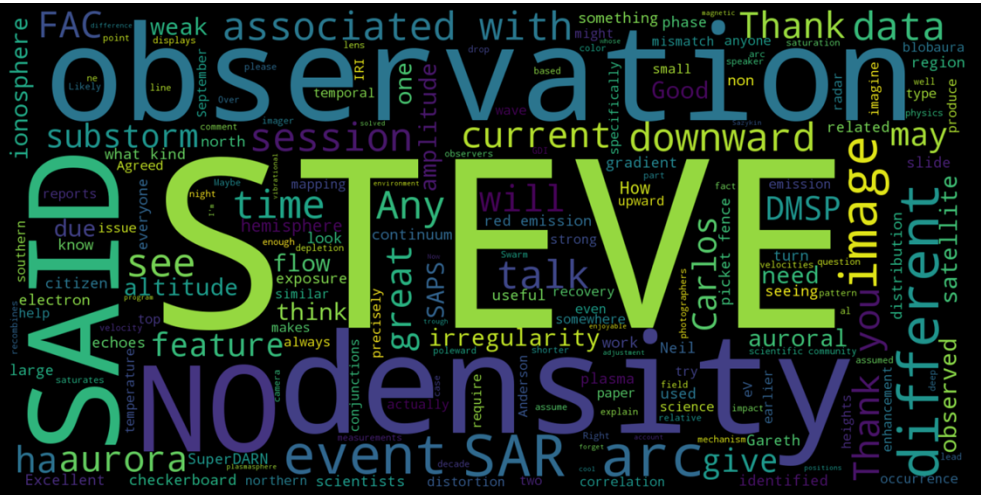
Aurorasaurus founder, NASA Goddard

Heliophysics Citizen Science Lead, NASA HQ

Photo: Mt. Assiniboine and STEVE by Jun Wang, Alberta Aurora Chasers, American Scientist magazine

Acknowledgements

- Citizen scientists
- Scientists
- Aurorasaurus team members
- CEDAR session on YouTube: http://cedarweb.vsp.ucar.edu/wiki/index.php/2020_Workshop:Subauroral_Science
- Work in progress
- Collective work



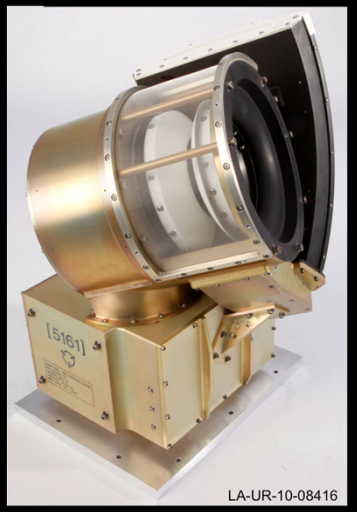
Word cloud, Bharat Kunduri

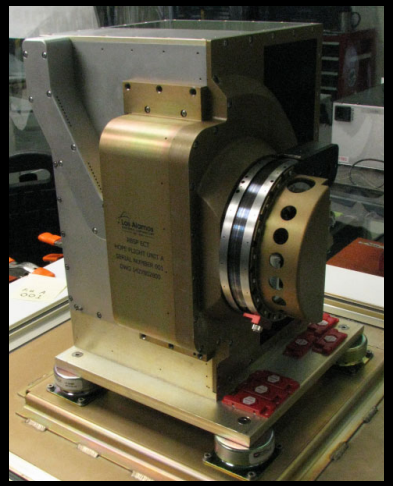
Outline

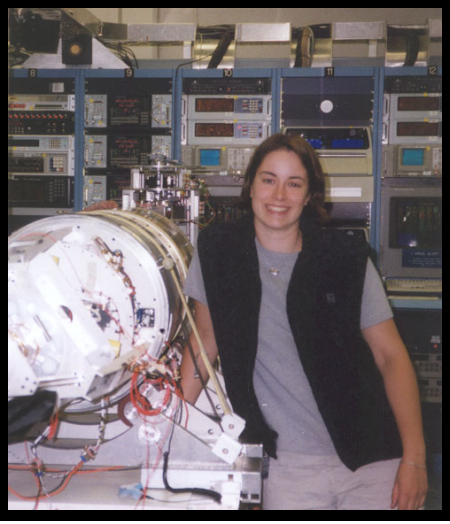
- Introduction
- What is STEVE?
- Some basic characteristics
- Ionospheric perspective
- Magnetospheric perspective
- Open questions

Who am I?

@spaceyliz







Now you know a little about me, I'd like to learn a little about you

- How many have seen aurora?
  - Half of the scientists have not
- How many are familiar with citizen science?

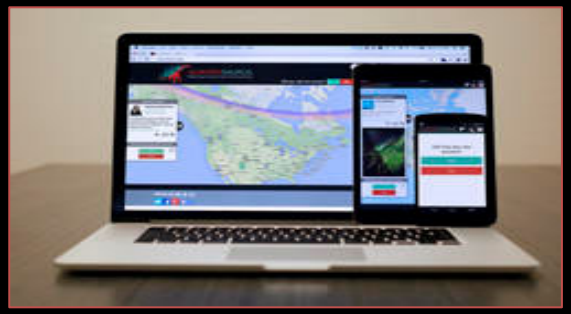
Ask yourself, why not?

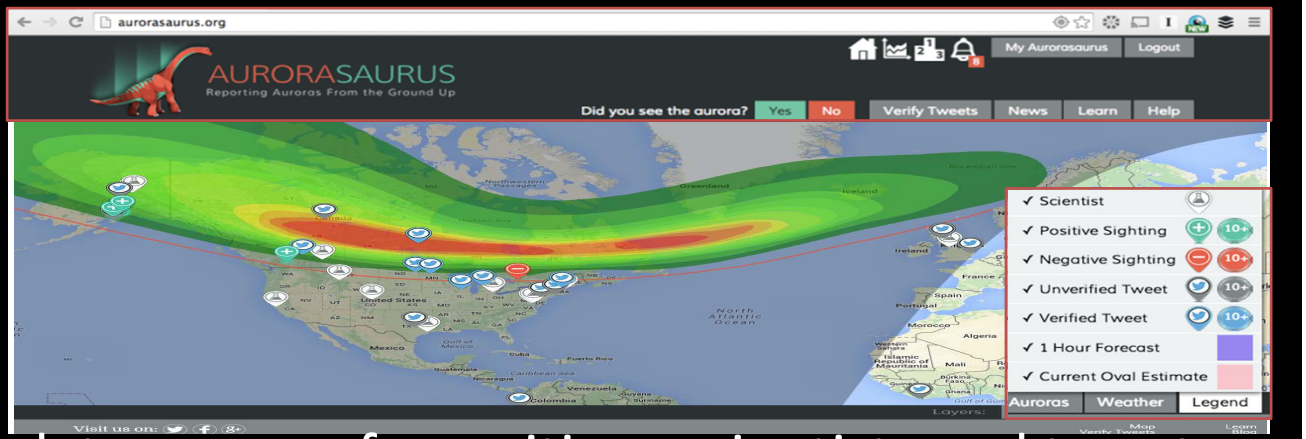
In 2011 I had a new idea about how ordinary people could help study aurora…

- What is Citizen Science?
- Why do we need help?

Aurorasaurus.org

Apple iOS & Android apps





New global, real-time data sources from citizen scientists and tweets
Alerts of auroral visibility for the public

Since 2014, our database has more than **7000** users, more than **7000** reports, and votes on more than **400,000** tweets.

Selected Papers (of >10 submitted so far)

MacDonald, E. A., et al., **Aurorasaurus: A citizen science platform for viewing and reporting the aurora**, Space Weather, doi: 10.1002/2015SW001214, 2015.

Case, N. A., et al., **Mapping Auroral Activity with Twitter**, Geophys. Res. Lett., 42, doi:10.1002/2015GL063709, 2015.

Case, N. A., et al., **Aurorasaurus and the St Patrick's Day storm**, Astronomy & Geophysics, 56 (3), 2015.

Case, N. A., E. A. MacDonald, and R. Viereck (2016), **Using citizen science reports to define the equatorial extent of auroral visibility**, Space Weather, 14, doi:10.1002/2015SW001320.

Tapia, A.; Lalone, Nicolas; (2014) **Crowdsourcing Rare Events: Using Beauty to Draw Participants into Science and Early Warning Systems**, 11th International Conference on Information Systems for Crisis Response and Management (ISCRAM). May 18-21, 2014

AURORASAURUS
Reporting Auroras From the Ground Up

Citizen Scientist Images
March, 2016

AURORASAURUS

NSF

New Mexico CONSORTIUM

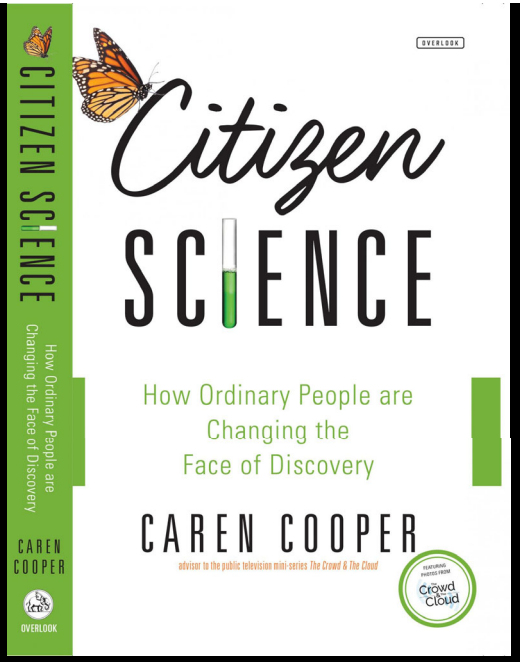
Science Education Solutions

A new, open innovation, geospatial, crowdsourcing, open source platform and public-private partnership…

POC: **Elizabeth MacDonald**, e.a.macdonald@nasa.gov

NASA Goddard

Aurora is not just a pretty picture, these data are useful



- Organized research in which members of the public engage in the processes of scientific investigations
  - Asking questions, collecting data, and/or interpreting results
- Works on a massive scale & generates high quality data
  - Leading to reliable, valid scientific outcomes & unexpected innovations

Citizen science has

- A multitude of scales and disciplines working together
- Dedicated communities & its own field of practitioners
- Terms of use / agreement for volunteer data
- Archives of data with FAIR data principles and additional concepts like interoperability of databases for multiple purposes
- Volunteer management & communication
- High quality data and controls
- Not free
- Science goals / questions appropriate to data quality

Citizen Science Association

Wiggins et al., 2018, Science Products Inventory

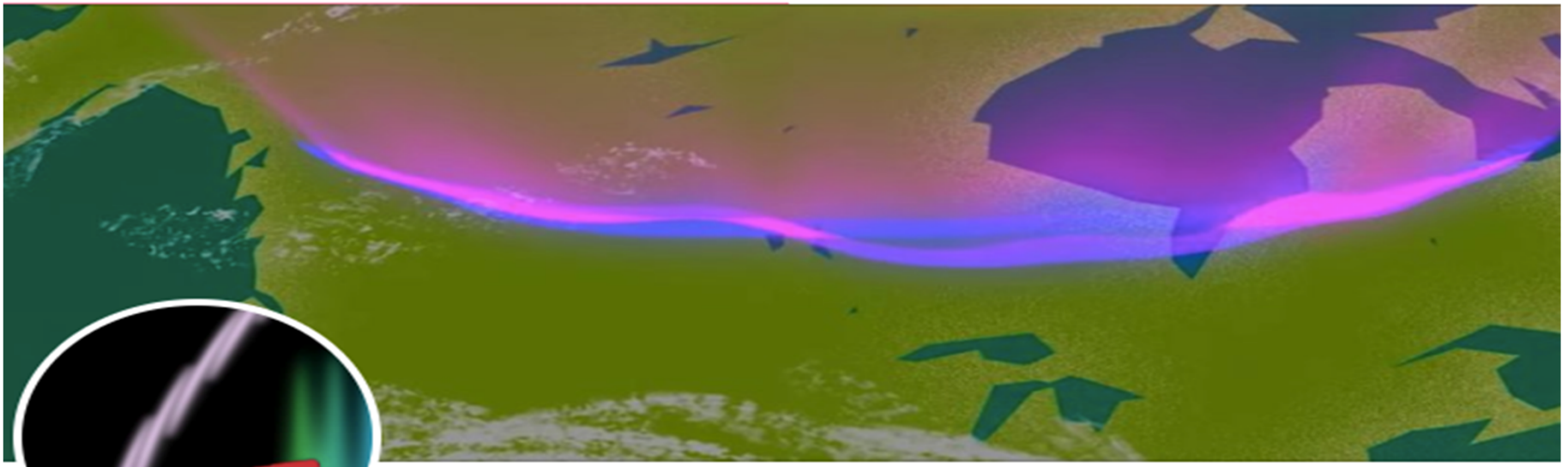
Citizen Science at NASA

- SMD has a policy encouraging citizen science (read SPD-33 guidance, bit.ly/spd-33)
  - Wherever appropriate for the science
- Heliophysics has a strategic working group on deliberate implementation of the policy
- Stay tuned! Much more to come
  - Virtual Summer of Citizen Science, 2nd annual NASA citsci meeting – starting May 27, archived
  - Cross-divisional opportunities, NSPIRES CSSFP in draft release
  - Guidance on best practices available

https://science.nasa.gov/citizenscience


Meet STEVE
• one type of subauroral arc
• optical manifestation of an extreme subauroral ion drift
• coolest creature of the night
Photo credit: Paulo Fedozzi

Home Moments Notifications Messages Search T



Tweets 362 | Following 164 | Followers 419 | Likes 1,409 | Moments 1

Phenomenal STEVE

@STEVEPhenomena Follows you

Just a misunderstood #StrongThermalEmissionVelocityEnhancement glitter bomb from the Sun

advances.sciencemag.org/content/4/3/eaa...

Joined September 2017

Tweets | Tweets & replies | Media

Pinned Tweet

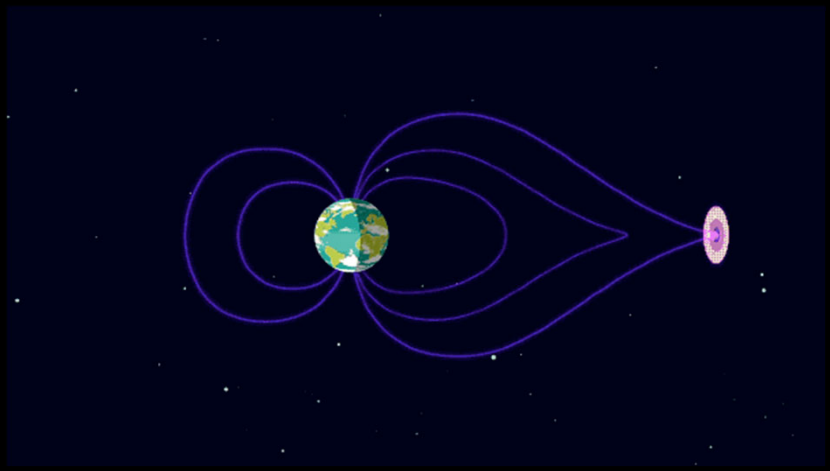
Phenomenal STEVE @STEVEPhenomena · Mar 16

Meet Steve, a new type of northern lights

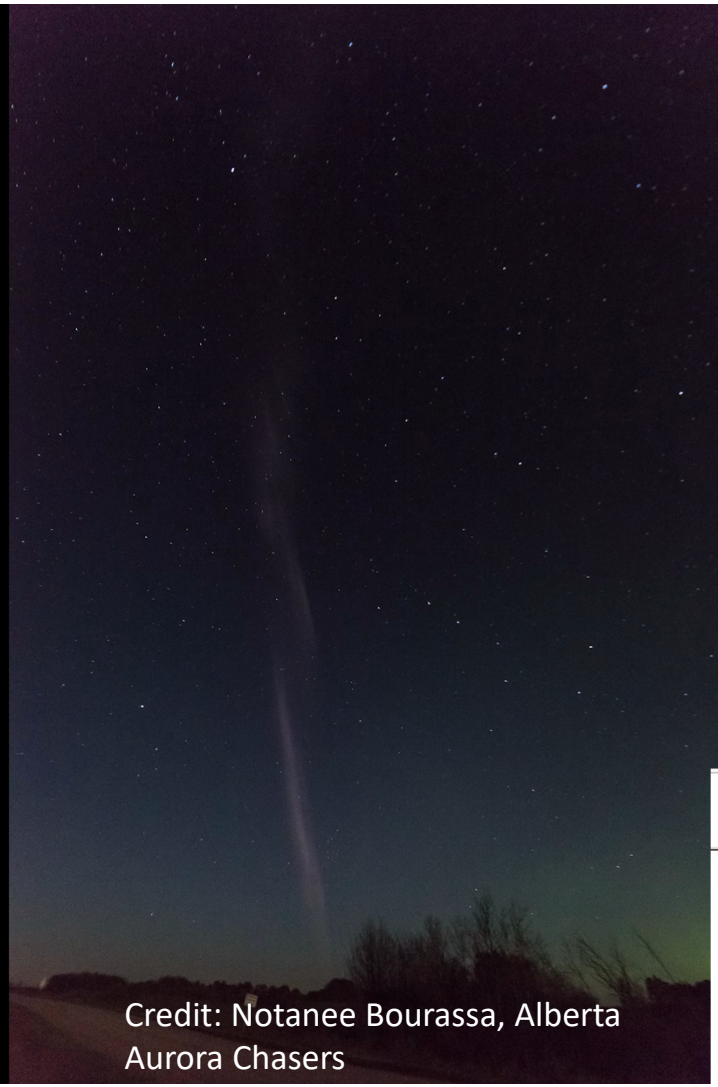
Science

The glowing ribbon of purple and green runs east-west in the sky. Citizen scientists in Canada weren't sure what

The story of STEVE



- NASA feature: https://www.nasa.gov/feature/goddard/2018/nasa-needs-your-help-to-find-steve-and-heres-how
- Eric Donovan's TEDxCalgary talk: https://www.tedxcalgary.ca/talks/how-i-met-steve-discovery-new-aurora
- Why it's really called Steve: https://www.youtube.com/watch?v=amwaFNZYUUY



Credit: Notanee Bourassa, Alberta Aurora Chasers

- Traditional science missed something
- Timelapse photos at lower than usual latitudes enable a different viewpoint

Common questions

- What are defining characteristics of STEVE?
- How does STEVE look to the naked eye?
- What the heck is an SAID (subauroral ion drift)?
- Is STEVE rare?
- What are the open questions?
  - Color, chemistry, turbulence, neutrals, radars, boundary significance
  - The secret to progress is holding loosely to our beliefs. We all have our own viewpoint/region/identity. Citizen science looks at our science with skill and without preconceived notions. More synthesis and system thinking is needed.


Meet STEVE
Sanjana Greenhill
Paul Zizka
Dave Markel
What do we already know about STEVE?
multiple emissions (purplish and green)
very narrow arc aligned east-west for hundreds of miles
occur in the subauroral region
last 20 min or even longer
faint but visible, can be photographed with 5-10 seconds exposure
Strong implication on STEVE's magnetospheric driver: long, thin, stable
Slide courtesy of Xiangning Chu

2016-07-25 05:52:30 UTC

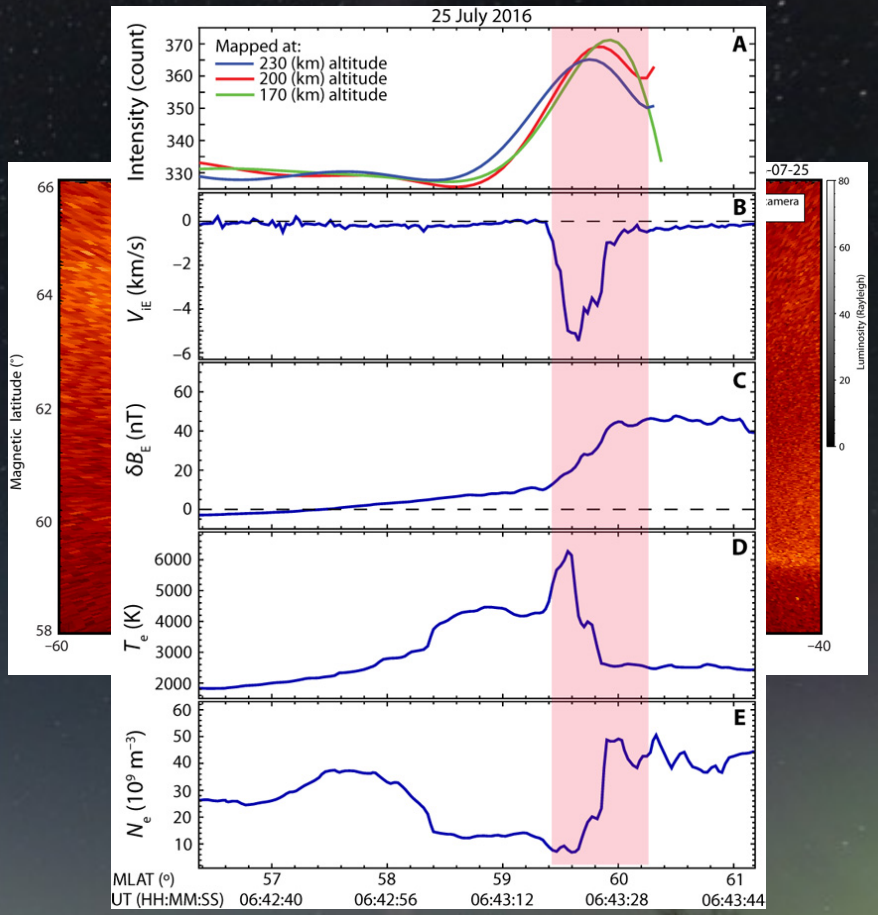
First scientific report

- STEVE is not new, that it has been observed for at least 50 years [Bailey et al., 2018, Hunnekuhl, 2019].
- STEVE occur in subauroral region
  - Located below proton aurora
- STEVE has Multiple emissions
  - Purplish continuous emission
  - Green picket fence emission
- STEVE is associated with SAID
  - Subauroral ion drift (SAID)
  - Strong westward ion flow
  - Magnetic perturbation
  - Electron temperature peak
  - Density gradient
- STEVE is backronym (Strong Thermal Emission Velocity Enhancement)

N

W

2016-07-25 06:03:51 UTC

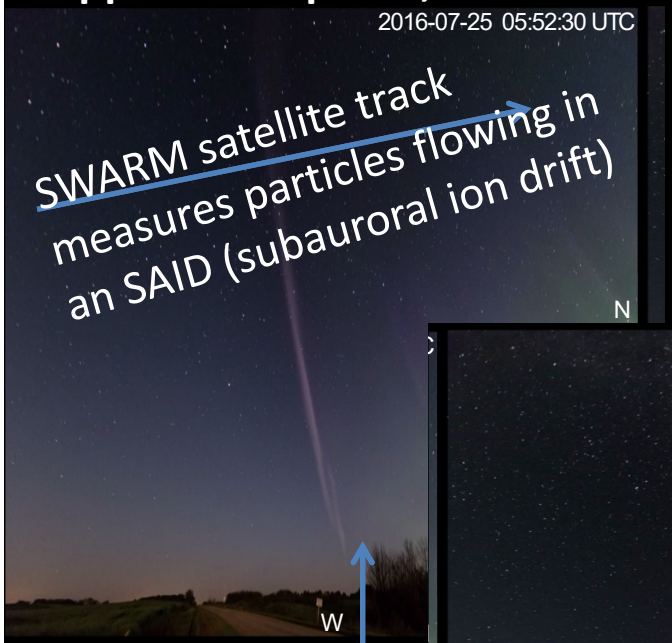


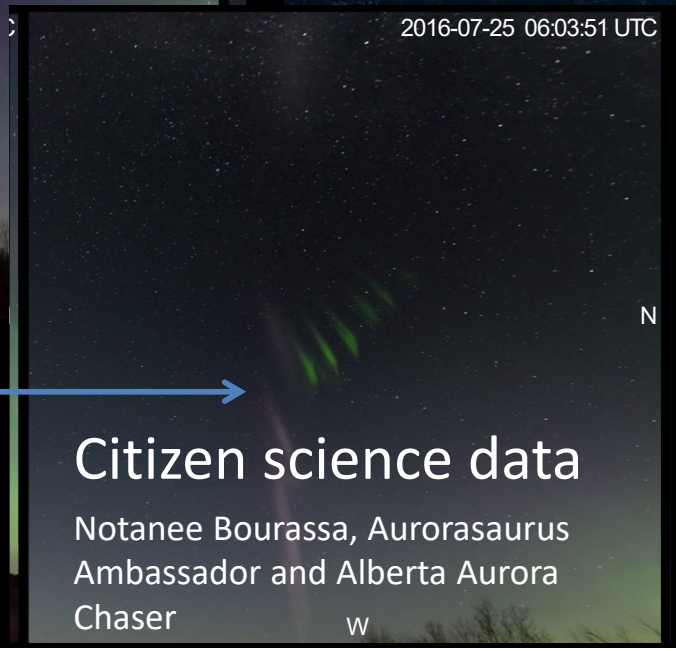
Slide courtesy of Xiangning Chu

MacDonald et al., 2018

New science in plain sight: Citizen scientists lead to the discovery of optical structure in the upper atmosphere, *Science Advances* 4, (2018).

Authors: E. A. MacDonald, E. Donovan, Y. Nishimura, N. A. Case, D. M. Gillies, B. Gallardo- Lacourt, W. E. Archer, E. L. Spanswick, N. Bourassa, M. Connors, M. Heavner, B. Jackel, B. Kosar, D. J. Knudsen, C. Ratzlaff, I. Schofield.

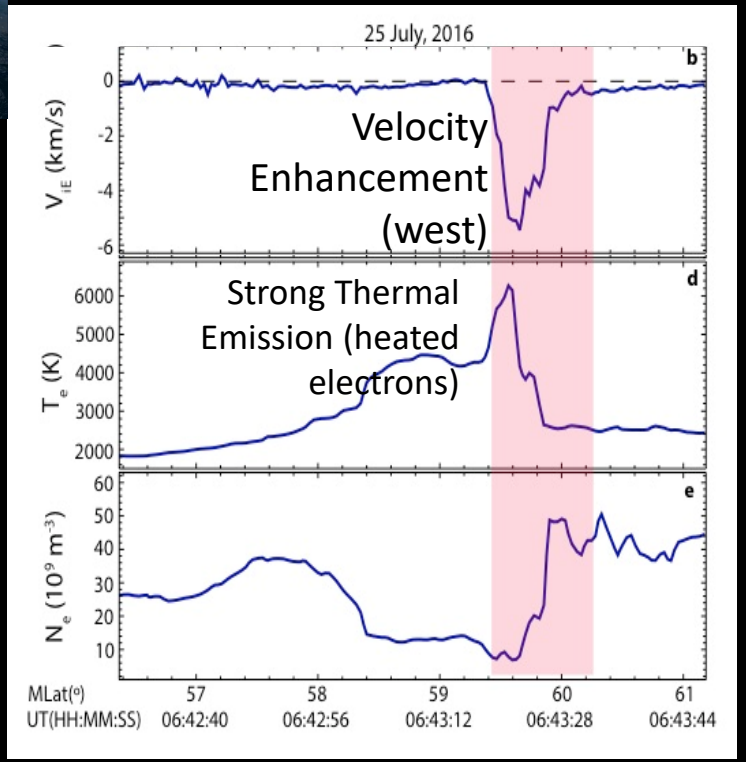




Satellite + ground-camera array + expert observers in conjunction

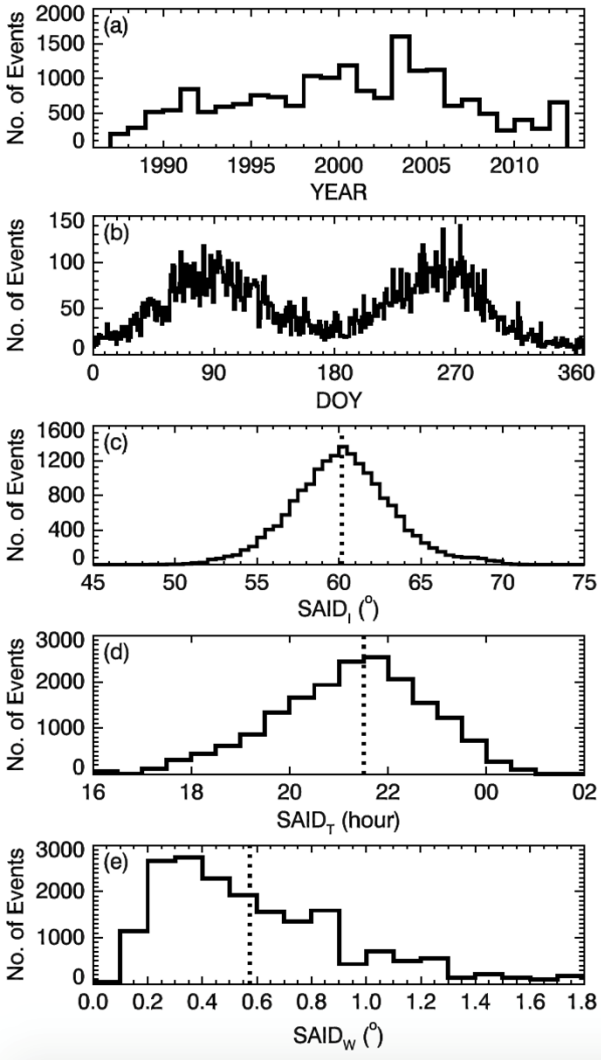
Citizen science data

Notanee Bourassa, Aurorasaurus Ambassador and Alberta Aurora Chaser



What is an SAID?

- Seen by satellites for 40 years
- Strong westward flow
- He et al., 2014 first statistical study looking at solar cycle, seasonal, diurnal variation



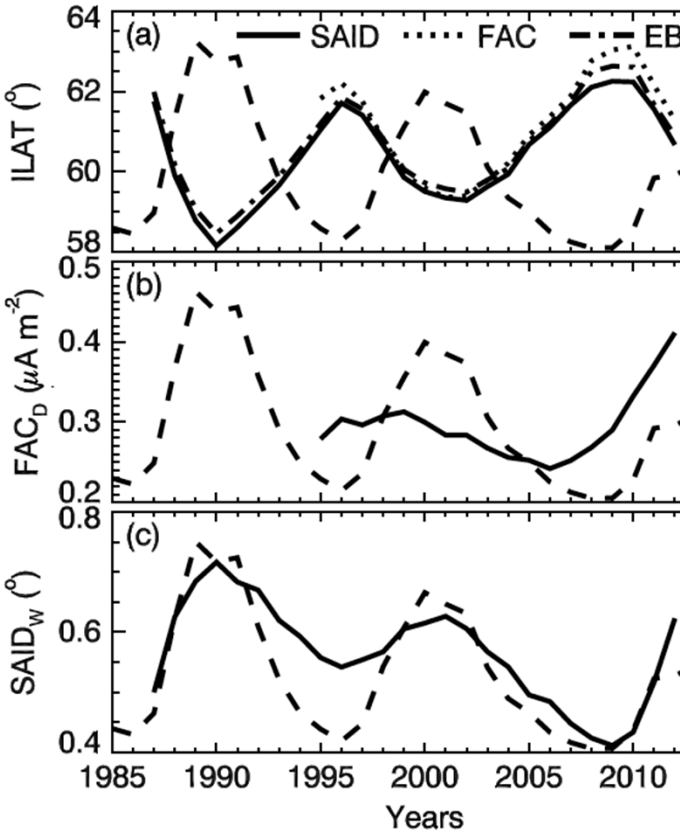
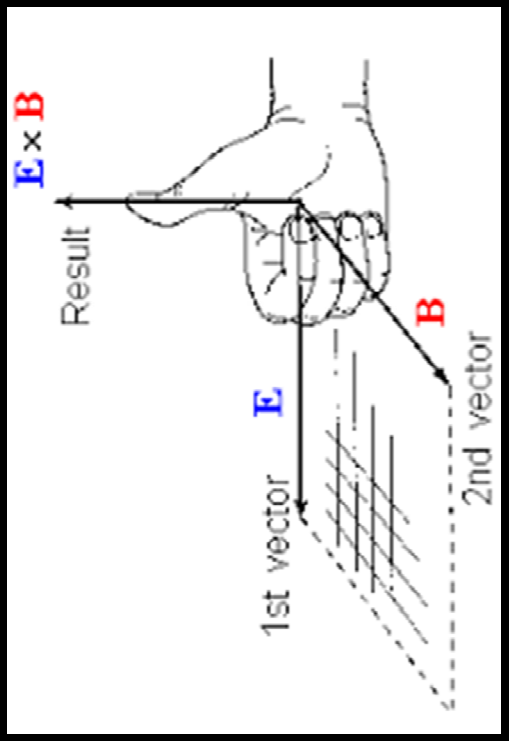


Figure 5. Solar cycle variations of SAID. Shown are the ye
(a) SAID$_I$ (solid line), FAC$_I$ (dotted line), and EBPE$_I$ (dash-do
FAC$_D$, and (c) SAID$_W$. Dashed lines in Figures 5a–5c repres
with axes displayed at right.

Why west??

- ExB drift
- Poleward electric field equals radially outward electric field in magnetosphere, driven by convection
- Right hand rule: fingers point to the pole (E) curl into B (into the pole in north), thumb points in direction of v



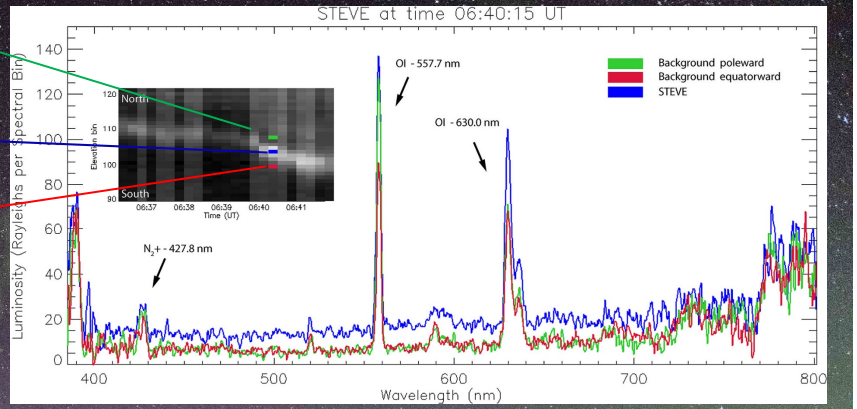
Rapid progress

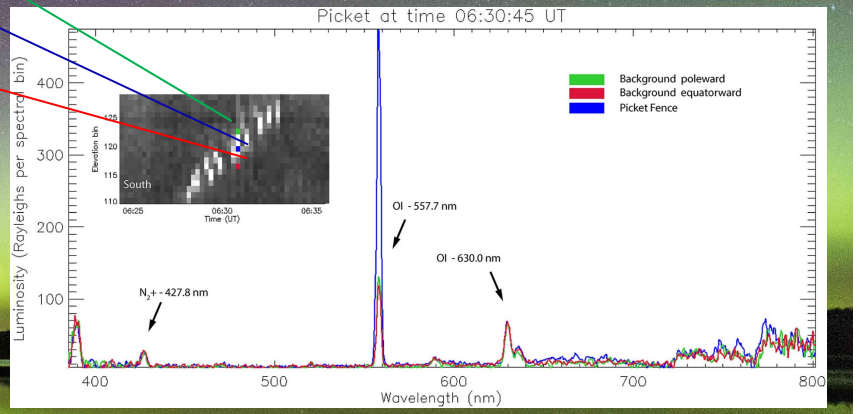
- Gallardo-Lacourt et al., 2018. STEVE statistical study – rare in THEMIS ASI, 28 events, correlation to the end of the substorm expansion phase
  - Largely consistent with SAID study
- Archer et al., 2019 – triangulation of heights
  - Consistent with Størmer 1900's
- Hunnekuhl results
  - STEVE not rare, STEVE not new, and more

Slide courtesy of Xiangning Chu

Optical spectra of STEVE

- Both SAR arc and STEVE captured by ground-based all sky imagers (ASIs)
- Multi-wavelength nature of **STEVE**
- **SAR** is red-line only
- **Continuous STEVE emission**
  - an enhancement of OI red-line (630 nm)
  - a continuum spans the visible wavelengths
  - the purple color of continuous STEVE is a result of this continuum.
- **Green Picket Fence emission**
  - a strong OI green-line (557.7-nm) emission similar to typical auroral emission
  - the green picket fence is a form of aurora
  - likely caused by particle precipitation



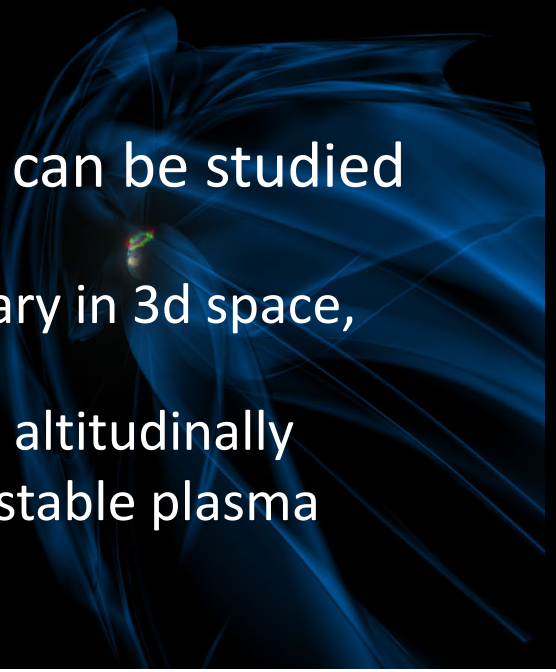


Gillies et al., 2019

What we now know

- STEVE lasts for ~an hour, observed from Canada/US border, Scotland, NZ, and Tasmania, seasonal peaks

- A well-studied phenomena can be studied in a new way.
  - Mapping a dynamic boundary in 3d space, must be modeled
  - Longitudinally, latitudinally, altitudinally
  - Constrain newly visible / testable plasma physics



Hunnekuhl Event List 1, published on *Open Science Framework*, with publications in process Note: rules of the road & cite data DOIs

- Manual worldwide collection with precision, quality control, and permission
- STEVE-related structures
  - ~800 single observations, ~200 observations days
  - Time, location, photos (for observers listed with name)
  - Manual collection, merging of lists, quality controlled
    - Permissions to citizen science data standards
  - Classification scheme, geomagnetic indices, & more
- Suitable for finding events with satellite and ground-based data
  - Covers last 2 solar cycles
  - Events with multiple observers, suitable for triangulation
  - Inter-hemisphere observations, 16 days, 3 near-simultaneous
- Merging lists with Aurorasaurus. Database / API in future

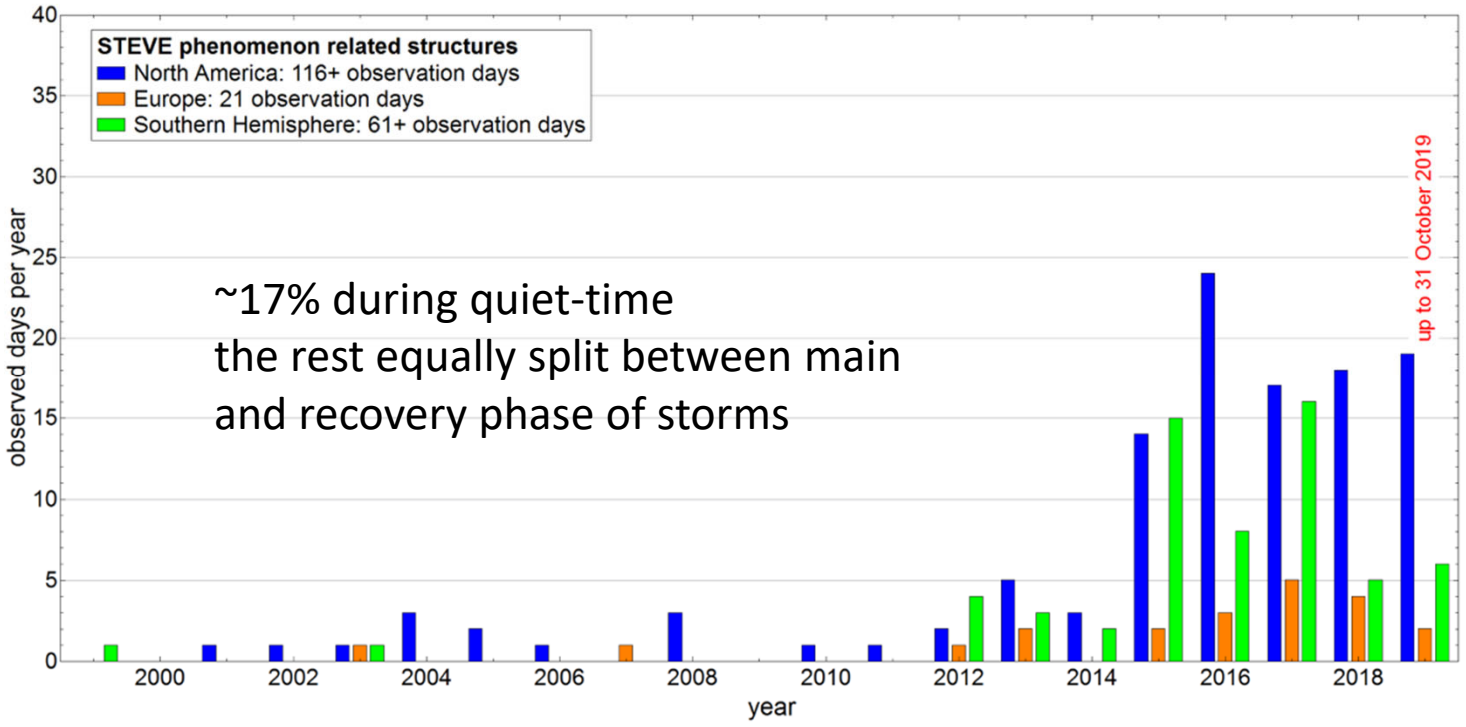
Observations from both hemispheres

UTC day	Country (Region) [observers]	Maximum time delay
08.10.2012	New Zealand [1] | Great Britain [3]	**~12 h**
29.06.2013	USA (Michigan) [1] | New Zealand [1]	Candidate, time for USA unclear.
17.03.2015	New Zealand [3] | Germany [4]	**~8 h 20 min**
16.08.2015	USA (Wisconsin, Minnesota) + Canada (British Columbia) [5] | New Zealand + Australia (Tasmania) [3]	**16 min**
11.09.2015	Canada (Alberta) [1] | New Zealand [1]	**3 h 11 min**
20.09.2016	USA (Alaska) [1] | New Zealand [4]	**18 min**
01.03.2017	Australia (Tasmania) [2] | Denmark [1]	**8 h**
03.03.2017	Canada (Alberta) + USA (Alaska) [5] | New Zealand [6]	**37 min**
28.03.2017	USA (Minnesota) [3] | New Zealand [1]	**8 h 10 min**
22.04.2017	Canada (Alberta) [2] | New Zealand [8]	**1 h 52 min**
28.05.2017	USA (Idaho, Iowa, Michigan, Minnesota, Montana, South Dakota, Utah, Wyoming) [12] | New Zealand + Australia (Tasmania) [9]	**2 h 42 min**
17.07.2017	Canada (Alberta) [2] | New Zealand [1]	**~3 – 3.5 h**
19.08.2017	Canada (Alberta, Saskatchewan) [4] | New Zealand [7]	**6 h 27 min**
22.08.2017	Canada (Manitoba, Ontario, Saskatchewan) [5] | New Zealand [1]	**~8 h 30 min**
31.08.2019	Canada (Alberta, Saskatchewan, Yukon) + USA (Minnesota, Washington) [19] | New Zealand [4]	**2 h 53 min**
01.09.2019	Canada (Alberta, British Columbia, Saskatchewan) + USA (Michigan) [5] | New Zealand [2]	**1 h 50 min**
28.09.2019	USA (Alaska) [3] | Australia (Tasmania) [1]	**3 h 45 min**

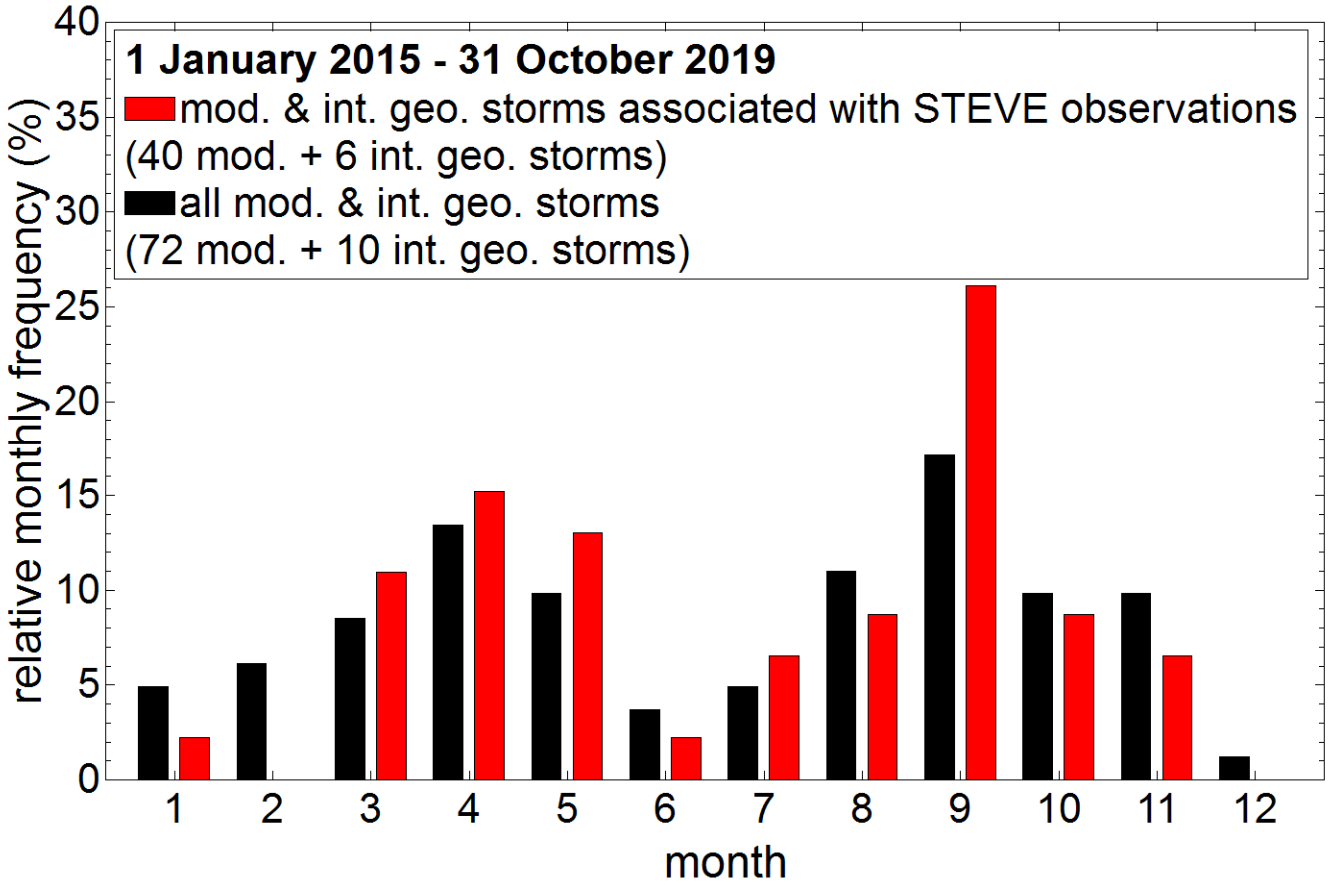
- Event list contains 16 days with observations from the Northern and Southern Hemisphere + 1 further candidate
  - 3 days with a maximum delay of 1 h, possibly conjugate observations
  - 7 days with a maximum delay between 1 and 4 h, possibly linked to subsequent substorms
  - 5 day with a maximum delay between 4 and 9 h
  - 1 day with a maximum delay of ~ 12 h
- Nishimura et al. (2019) report on first conjugate STEVE observation, observed on 8 May 2016
- It is currently unknown how many STEVEs occur as conjugate STEVEs
- Amateur observations can help to identify conjugate observations

Worldwide reports on STEVE sightings have increased dramatically since 2015

Factors: solar cycle, media, citizen science, not absolute rates, geographic coverage limits



Seasonality of STEVE at subauroral latitudes



STEVE is not new

- 100 yr old STEVE observations and papers have been uncovered by an amateur professional aurora historian in Germany
- Famous Norwegian scientist Carl Størmer researched “feeble homogenous arcs of great altitude” with atypical spectra

Hunnekuhl and MacDonald, Space Weather, March 2, 2020

Top Photo: Størmer C. (1935). Remarkable Aurora-Forms from Southern Norway. I, Feeble Homogeneous Arcs of Great Altitude, Geofysiske Publiskasjoner, 11(5)

What about the little green facets?

- Fascinating fundamental plasma physics MUST be explained. Field lines not vertical. Horizontal and vertical drift.

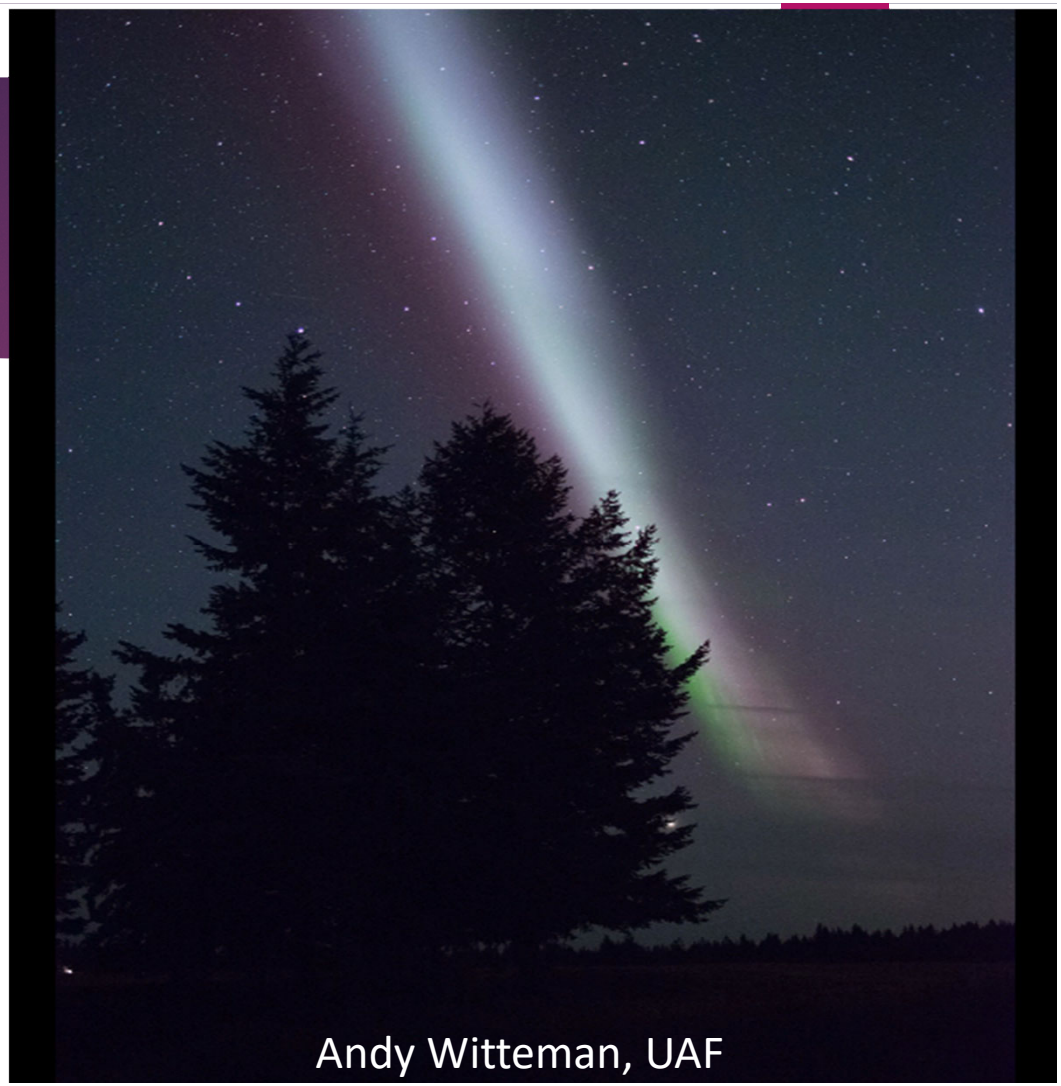
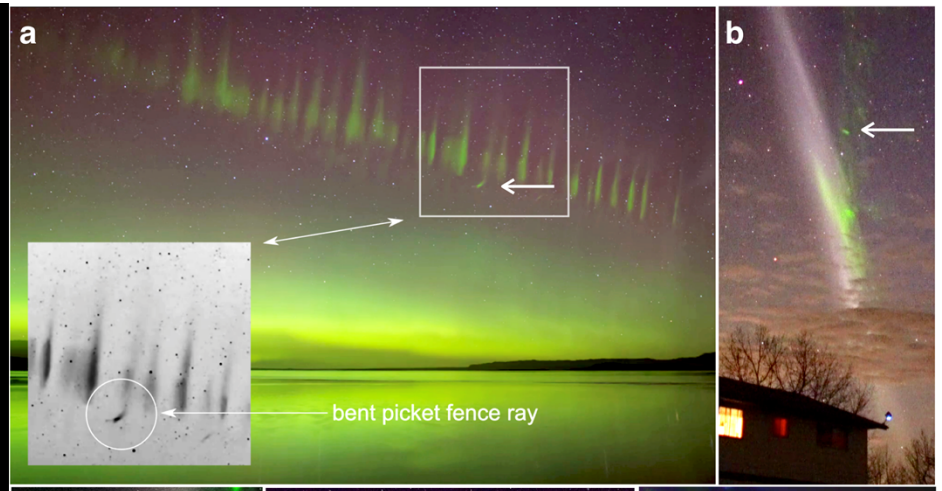
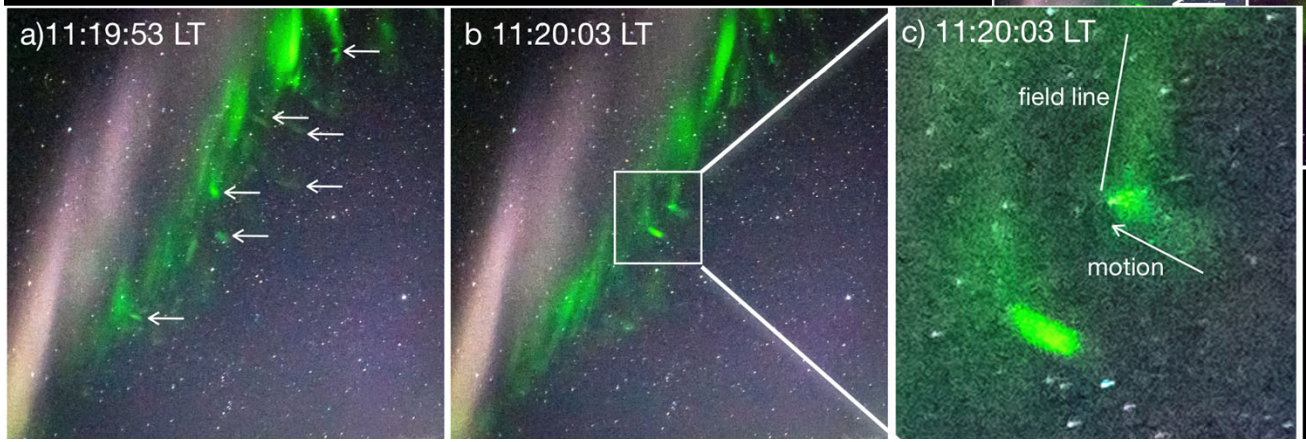



Photo Credit: Alexei Chernenkoff

Mysterious green streaks below STEVE

Semeter et al., 2020, AGU Adv., under revision (*ESSOAR preprint*)





a) 8-s exposure, courtesy Stephen Voss b,c) 5 s, Alexei Chernenkoff d) 3 s, Neil Zeller e) 40 ms, Bogden Carasava

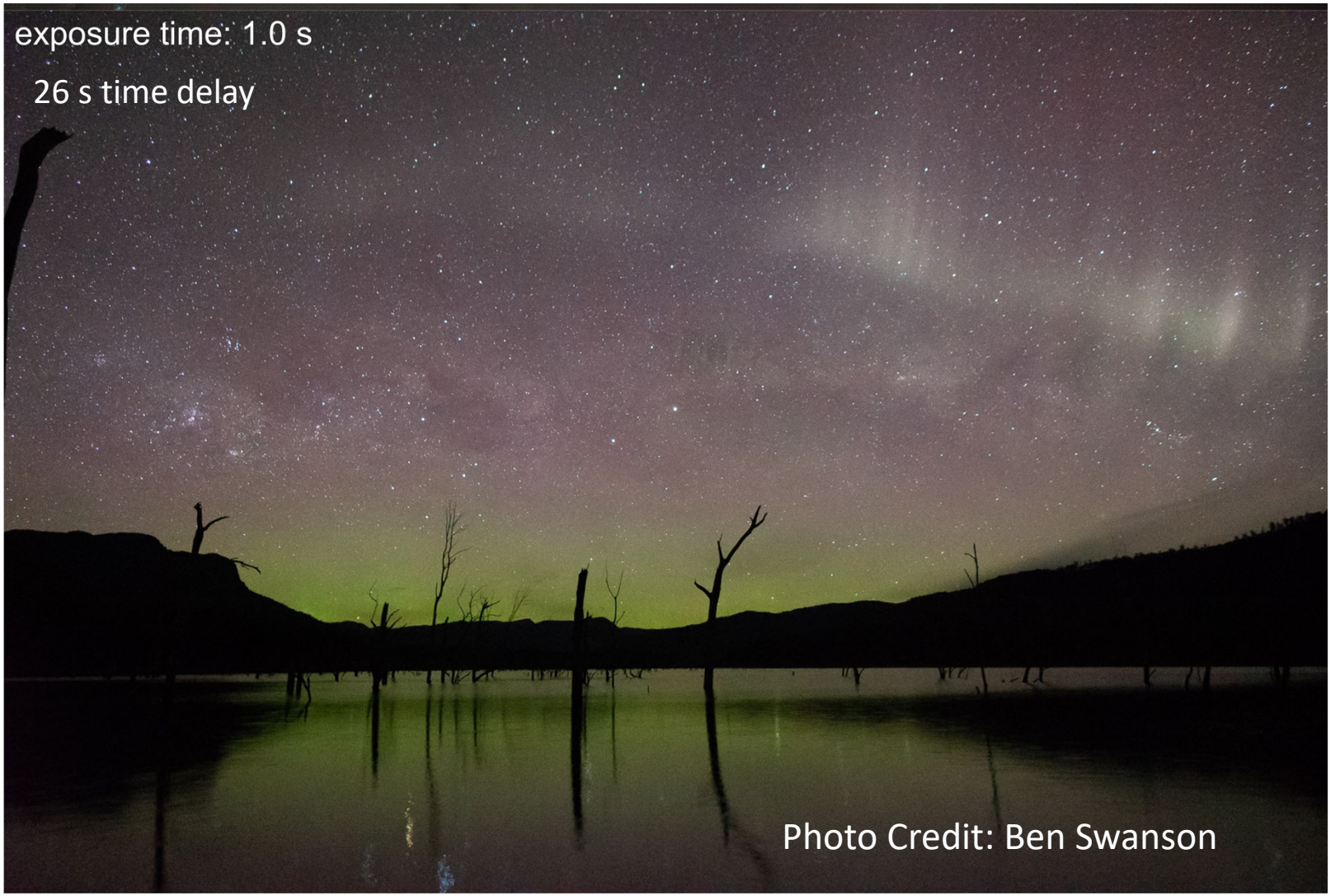
Further work on the ITM side

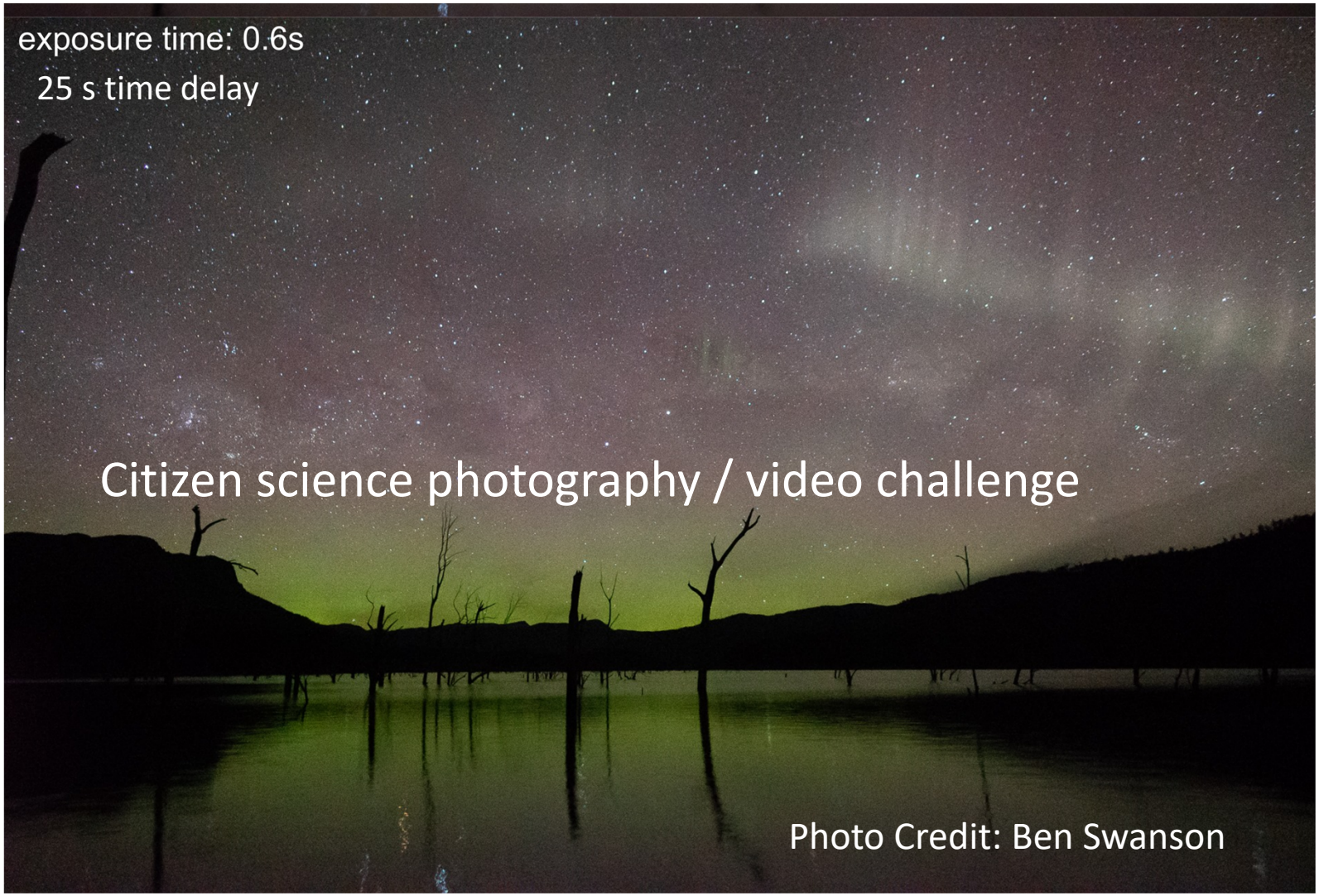
- What causes these events (from our traditional observations) is not yet clear
  - Conjunctions rare
- However, some of the strongest drifts & very complex dynamics are newly visible plasma physics
  - Simulations, models
  - Farley Buneman, Ionospheric Alfven Resonator with tearing mode unstable current sheets, Ionospheric Feedback Instability, $\nabla n \times \nabla T$ instability, current convective instability, thermomagnetic instability
- Not yet modeled regularly

Alan Dyer, AAC

Best video, Neil Zeller

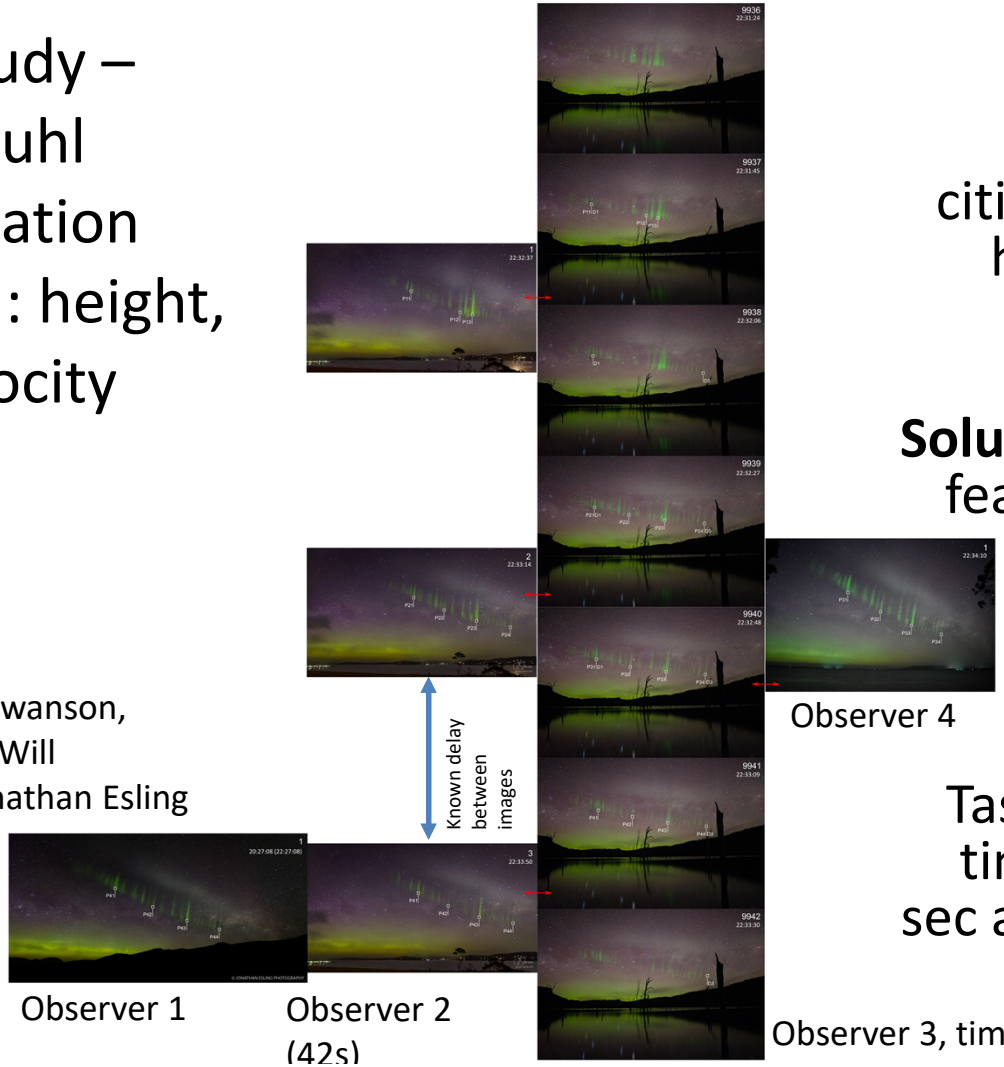

exposure time: 2.5 s
Exposure time exposes new features…
Photo Credit: Ben Swanson


exposure time: 1.0 s
26 s time delay
Photo Credit: Ben Swanson


exposure time: 0.6s
25 s time delay
Citizen science photography / video challenge
Photo Credit: Ben Swanson


Exposure time 0.6 sec
Photo Credit: Ben Swanson

Case Study – Hunnekuhl triangulation method: height, and velocity



Credits: Ben Swanson, James Stone, Will Standring, Jonathan Esling

Problem: accurate triangulation requires simultaneous images but citizen science images are ad hoc and camera clocks can vary by minutes

Solution: tracking picket fence features & motion, spherical trigonometry, Vincenty algorithm for geodesics

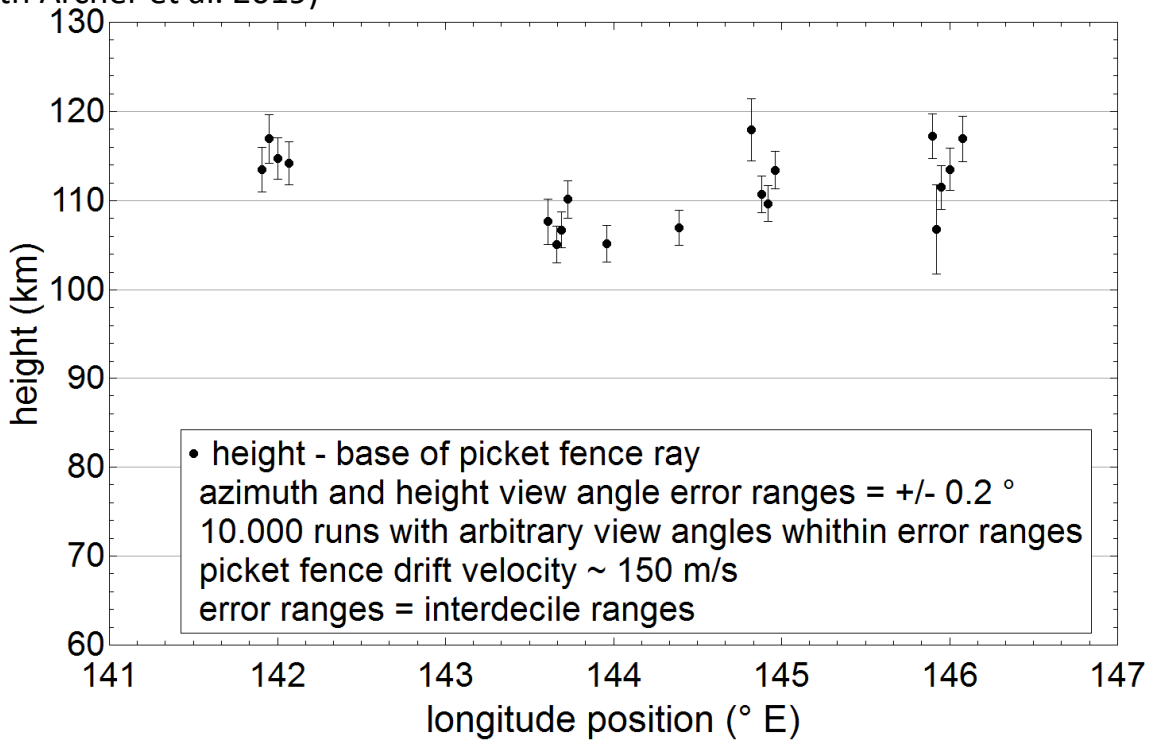
Example: Nov. 7, 2015, 4 Tasmanian observers, 1 with time series, and images ~20 sec apart (though cameras say ~min. apart)

Triangulation case study results

Picket fence heights derived for 4 rays and 5 observer pairs for ~1 minute 20 seconds
19 mean heights 105.1 – 117.9 km
Picket fence velocity (2 vertical rays tracked over ~2 minutes)
156 +/- 6 m/s, 146 +/- 5 m/s (consistent with Archer et al. 2019)

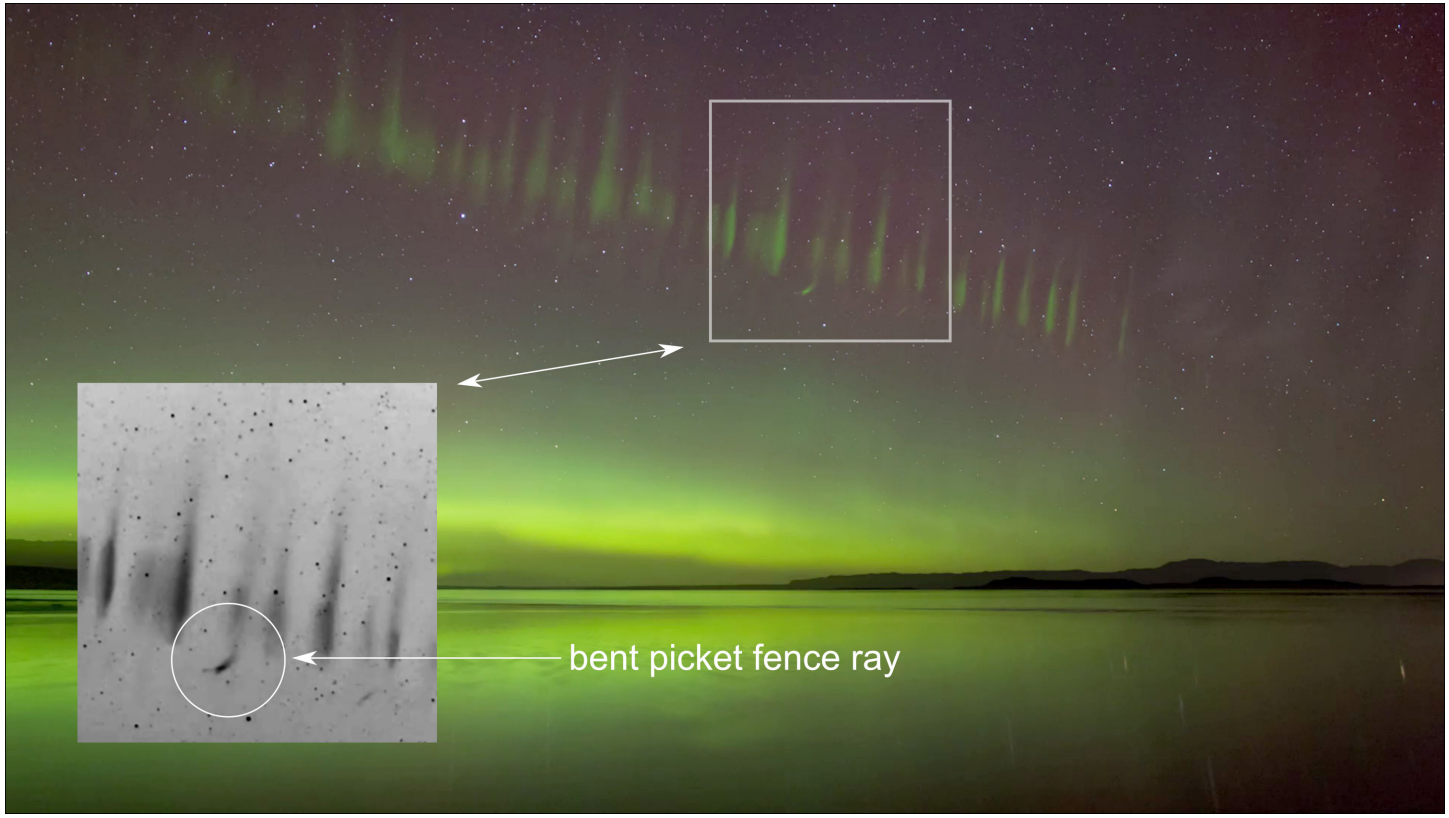
- STEVE white vertical ray substructure velocity (visible for ~10 seconds)
  9.9 +/- 0.2 km/s tracked over ~8 sec (consistent with SAID drift speeds)

- Uncertainty quantification on these techniques
  - Location, azimuth errors tracked with Monte Carlo method
  - Can identify critical cases where triangulation doesn't work



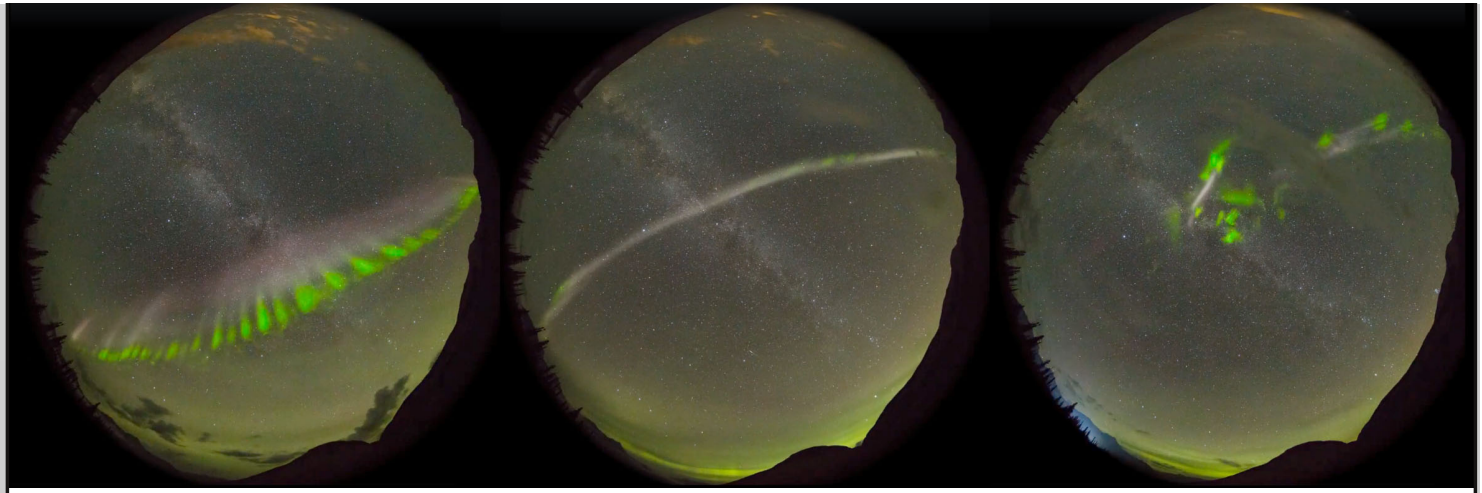
Poleward ‘bent’ structures, rare?

Mar 27, 2017 New Zealand, Credit: Stephen Voss



Overview

- “Am-pro” collaborations contribute VALUABLE data and analysis to our understanding of characteristic features of STEVE phenomena & related structures



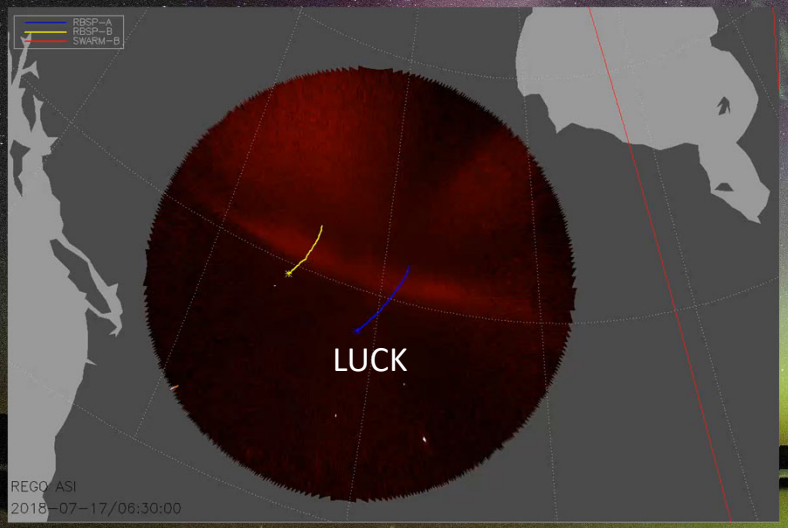
31 August 2019, Canada (Alberta), images from time lapse: Mike Gere
left: STEVE arc with purple upper and whitish lower arc, picket fence beneath STEVE arc
middle: STEVE arc and picket fence magnetically overhead,
right: chaotically structured picket fence following turbulent STEVE arc dynamics

STEVE on 2018-07-17- magnetospheric implications

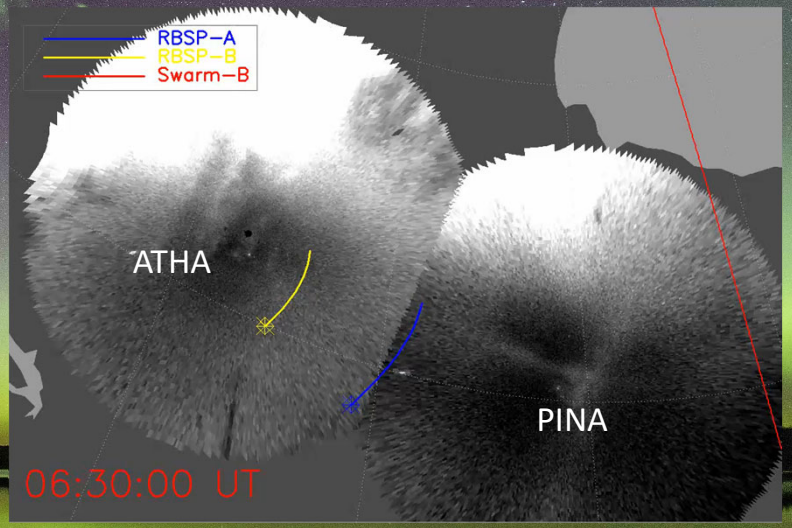
Slide courtesy of Xiangning Chu

STEVE on 2018-07-17

- **Ground**: both SAR arc and STEVE captured by all sky imagers (ASIs)
- **Ionosphere**: Swarm-B crossed to the east of STEVE
- **Magnetosphere**: Van Allen Probes' footprints crossed STEVE, **directly**



Redline-only REGO ASI at LUCK

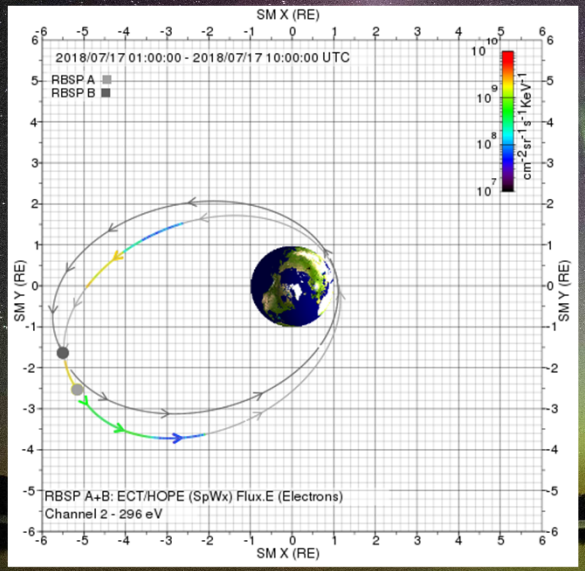


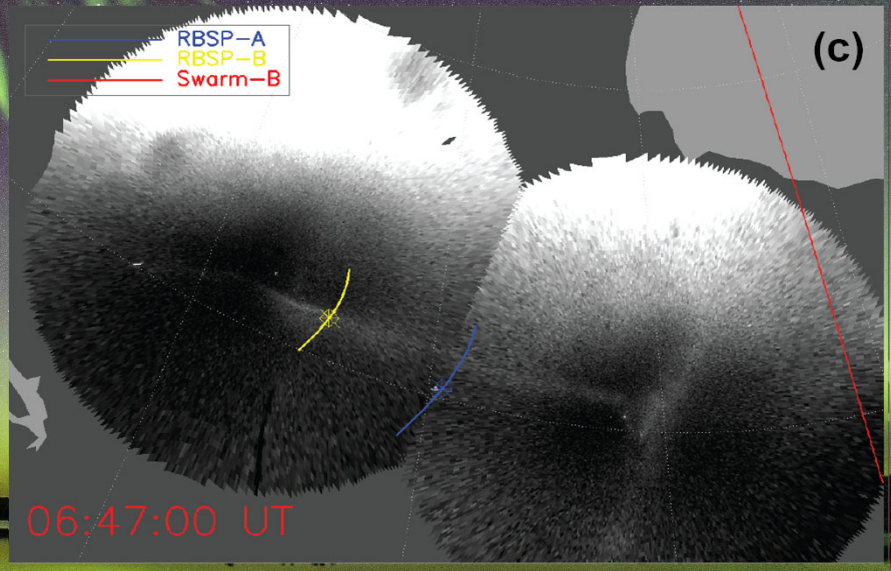
White-light THEMIS ASIs at ATHA and PINA

Chu et al., 2019

Magnetospheric driver: Van Allen Probes observation

- Van Allen Probes' footprints **directly crossed** STEVE and the plasmapause at exactly the same time.





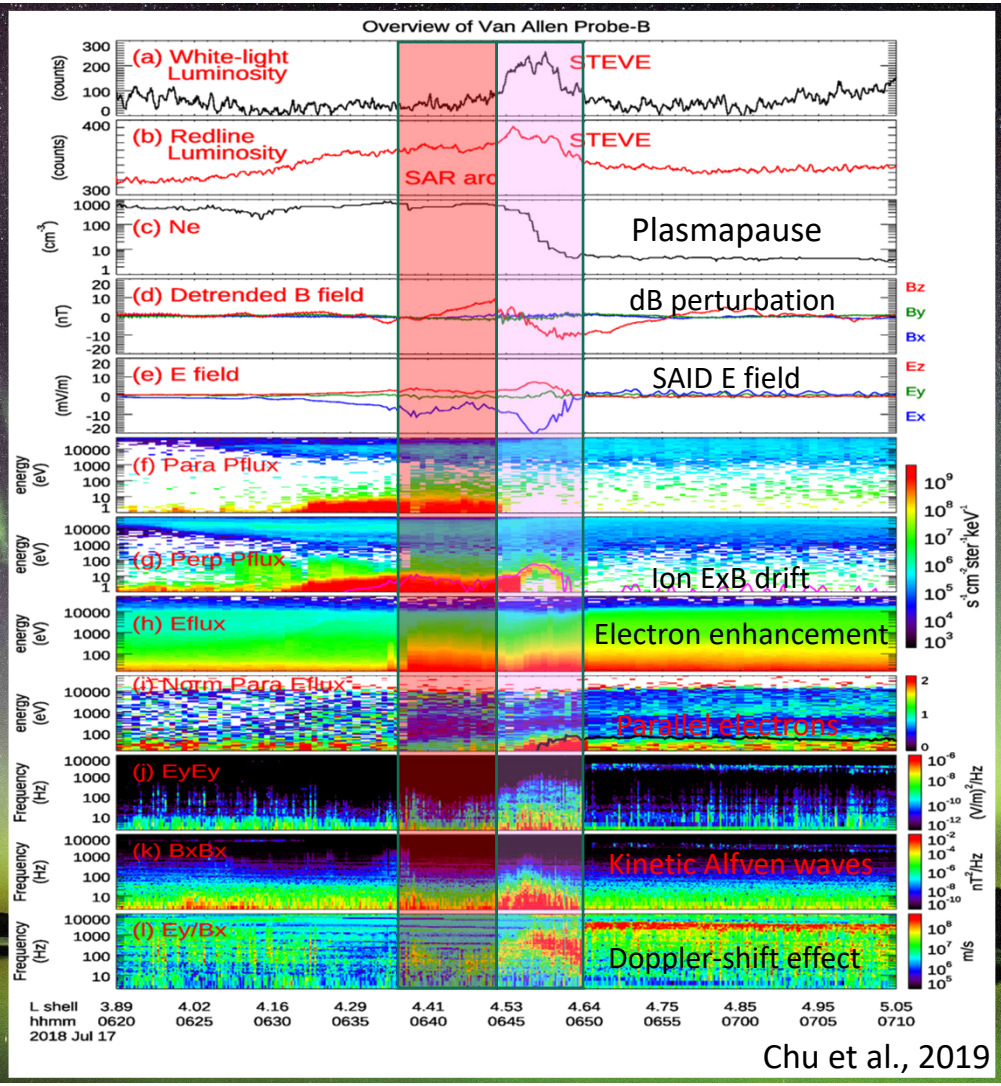
Slide courtesy of Xiangning Chu

Chu et al., 2019

Magnetospheric driver

- Van Allen Probes' footprints directly crossed STEVE and the plasmapause at exactly the same time.
- STEVE maps to
  - Sharp plasmapause: long, thin, stable
  - explains STEVE's appearance:
  - Magnetic field perturbations
  - Large electric fields
  - Strong Kinetic Alfven waves (KAW)
  - Parallel electron acceleration by KAW
  - Ion perpendicular drift
- SAR maps inside the plasmapause
  - Isotropic electron acceleration via Coulomb collisions with ring current population
- STEVE, SAR arc, SAID, ion/electron acceleration, KAW at/near the plasmapause (PP), which is a waveguide.

Slide courtesy of Xiangning Chu

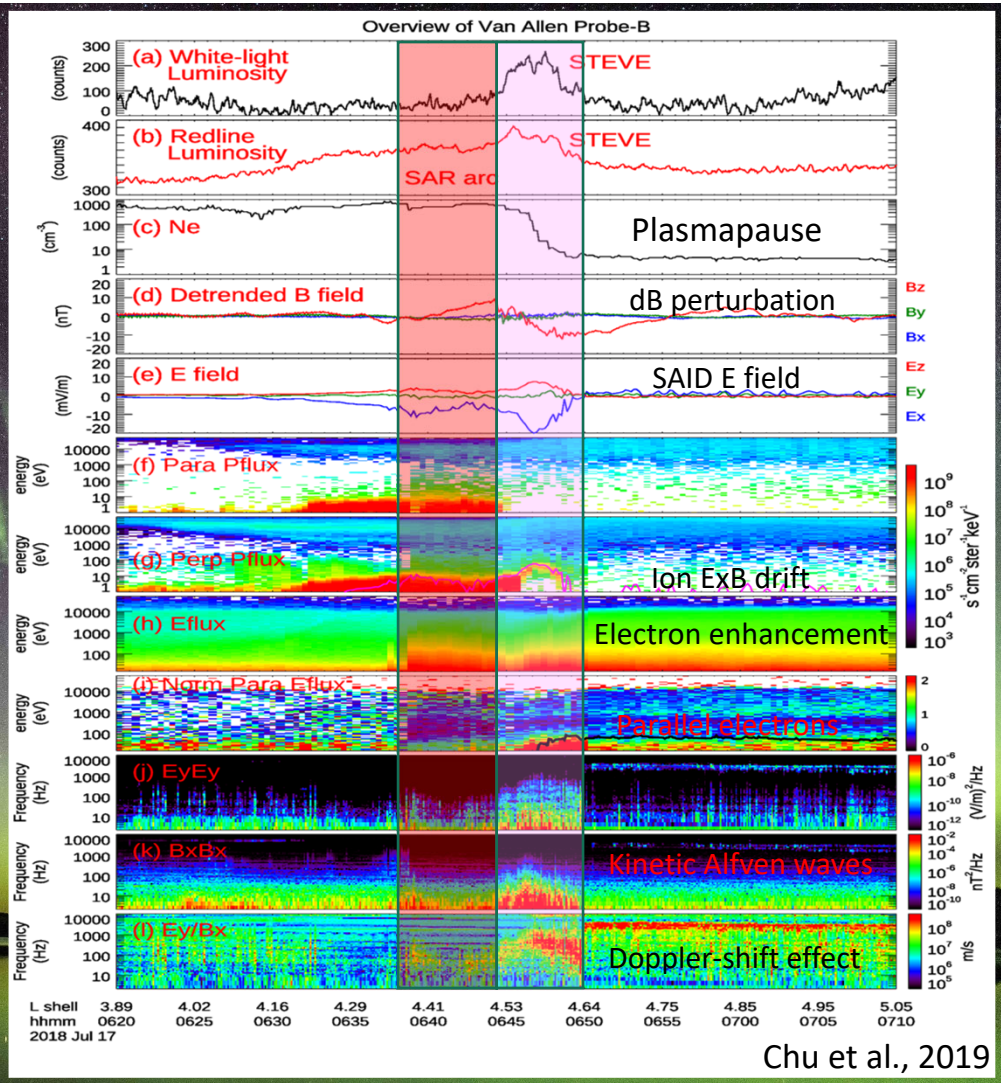


Chu et al., 2019

Magnetospheric driver

- Van Allen Probes' footprints directly crossed STEVE and the plasmapause at exactly the same time.
- STEVE maps to a sharp plasmapause
- SAR maps inside the plasmapause
- STEVE, SAID, ion/electron acceleration, KAW, SAR arc at/near the plasmapause (PP), which is a waveguide.
- SAR arc generated electron heating by heat flux from isotropic electron heating inside the PP
- Continuous STEVE by superposition of heat flux, electron precipitation or local ionospheric processes
- Green picket fence by electron precipitation generated by low-energy parallel electron and further acceleration by Alfven waves (auroral acceleration process)

Slide courtesy of Xiangning Chu

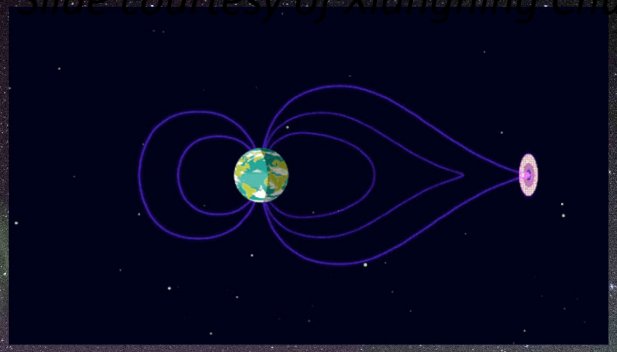


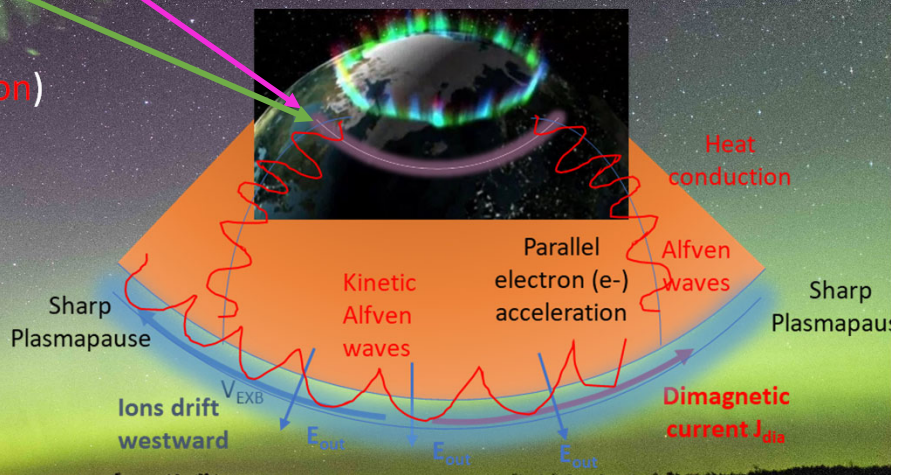
Chu et al., 2019

Meet STEVE

Slide courtesy of Xiangning Chu

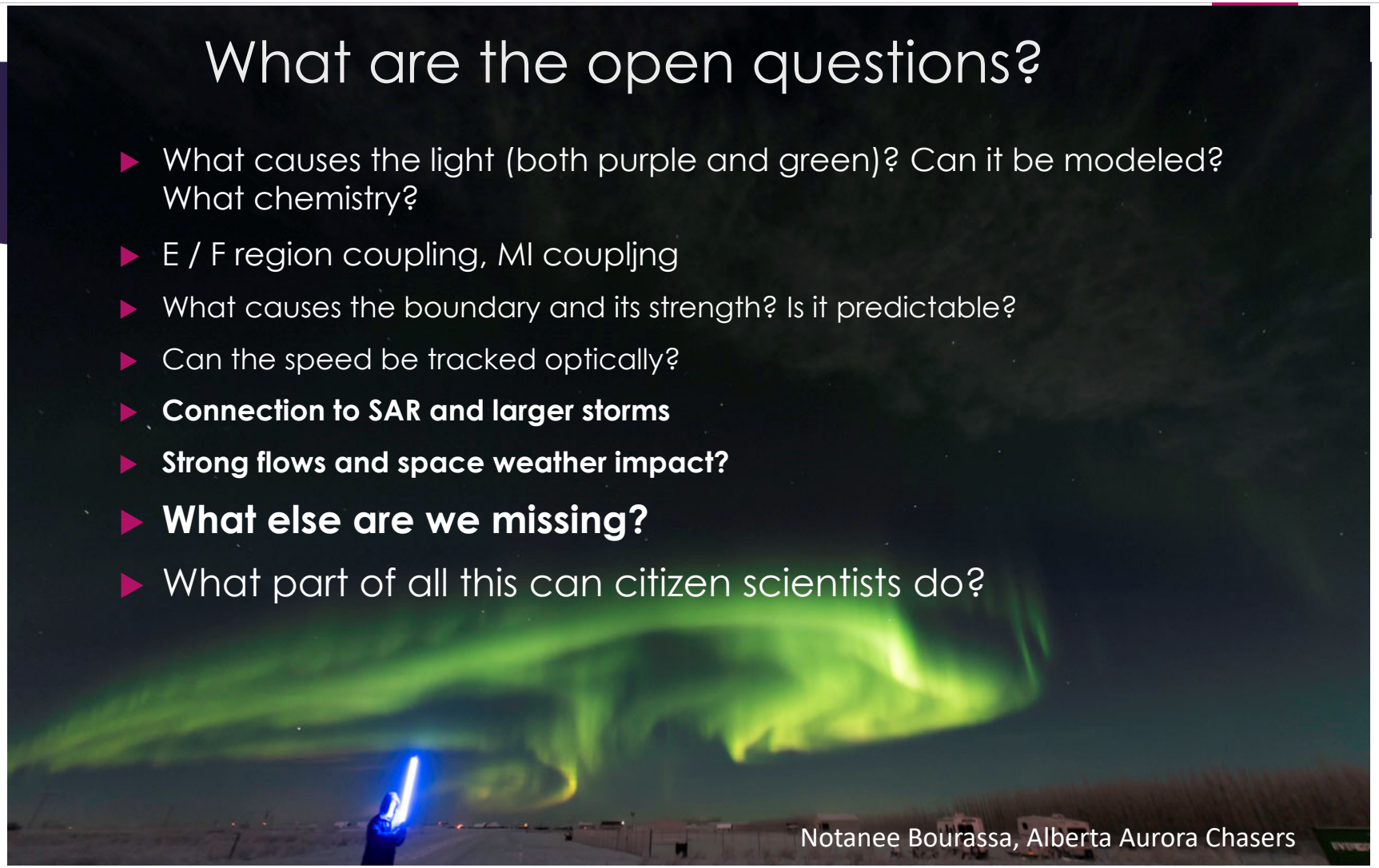
1. STEVE is just reported in the science community
2. STEVE observed in the *subauroral* region
3. STEVE has two types of emissions
   1. Purplish continuous emission (**redline** + **spectral continuum**)
   2. Green picket fence structure (**green aurora**)
4. STEVE is different from SAR (redline only)
5. Ionospheric features of SAID:
   1. Electron heating (can generate visible red emission)
   2. Electric field, FAC and density gradient
6. **Magnetospheric driver region** (SAID):
   1. Sharp plasmapause
   2. Electric field
   3. Westward plasma ExB drift
   4. FACs
   5. Strong KAW
   6. Parallel electron acceleration/electron heating
7. **Multi-wavelength continuous emission** by superposition of ~~**electron heating by heat flux**~~, **electron precipitation, or local ionospheric processes**
8. **Green picket fence** by **electron precipitations** accelerated by auroral acceleration process (KAW)





What are the open questions?

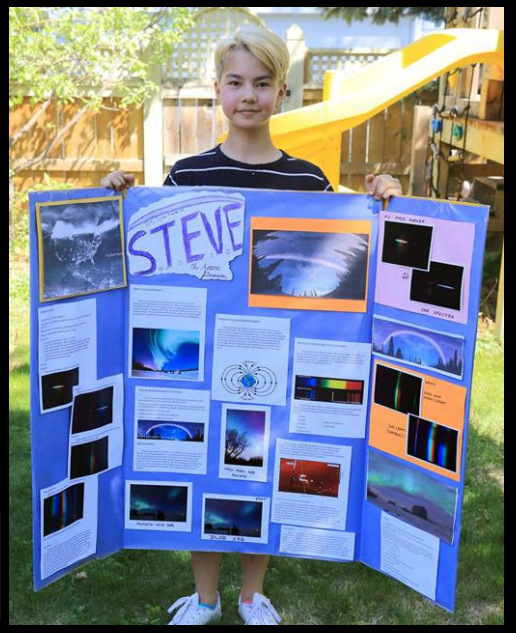
- What causes the light (both purple and green)? Can it be modeled? What chemistry?
- E / F region coupling, MI coupljng
- What causes the boundary and its strength? Is it predictable?
- Can the speed be tracked optically?
- **Connection to SAR and larger storms**
- **Strong flows and space weather impact?**
- **What else are we missing?**
- What part of all this can citizen scientists do?



Media coverage has helped recruit and reward citizen scientists

For Kids

- Wow in the World podcast on STEVE aurora
- Classroom webinar with Hearts in the Ice (Aurorasaurus on YouTube)
- Blog posts on DIY aurora, science fair, and high school activities
- Handouts and activities



NSSEC
NASA SPACE SCIENCE EDUCATION CONSORTIUM

For Adults

- US on Vimeo in April, Citizen Science Month

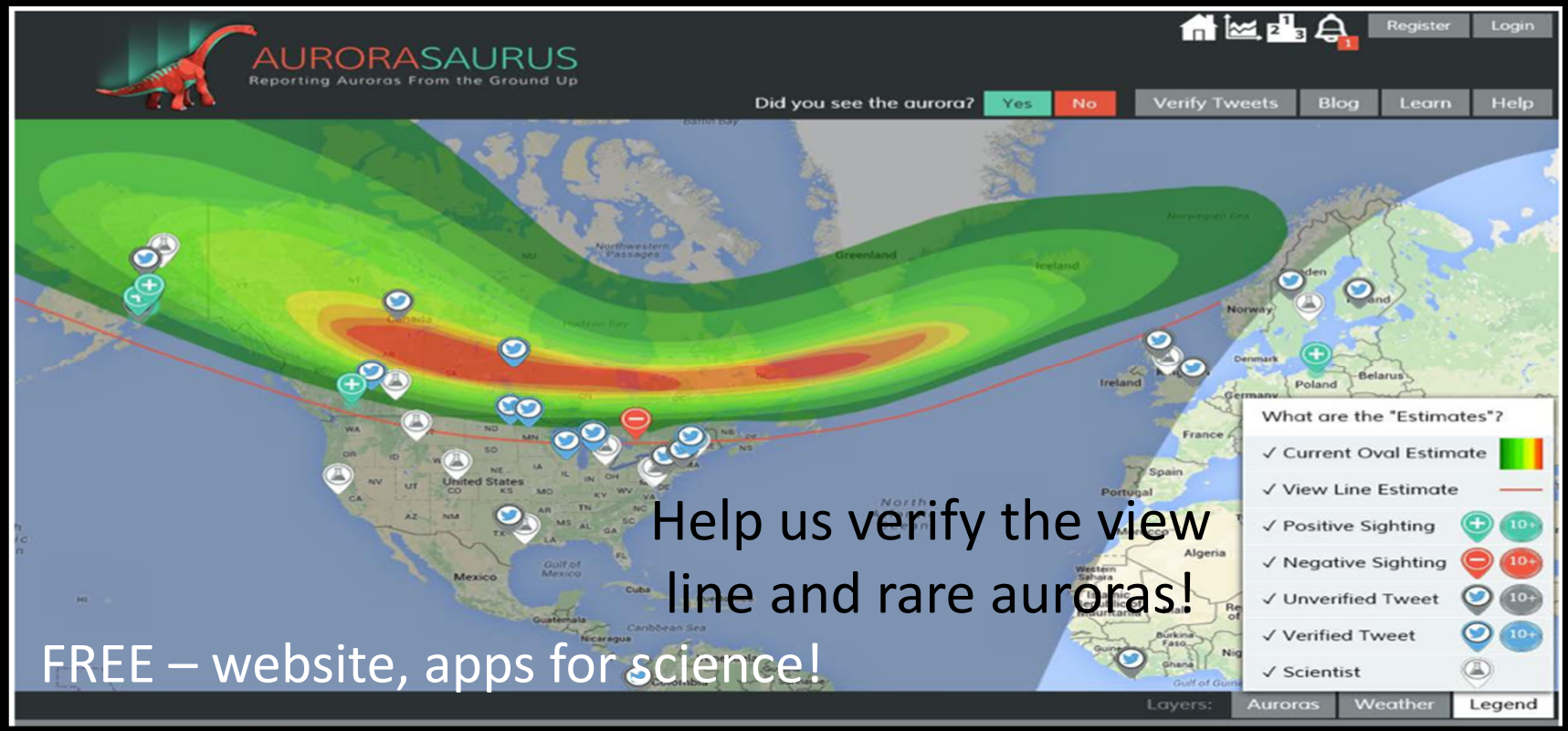
- Blog, newsletter, make reports, verify tweets
- Webinar with author Melanie Windridge ”Auroras: In Search of the Northern Lights” (YouTube)
- Educational & Ambassador opportunities

How a man behind the ‘Steve’ discovery used the Northern Lights to cope with life

Notanee Bourassa immersed himself in aurora borealis as a way to escape his troubles. One night, he saw something new and amazing.

by Meagan Campbell Mar 18, 2018

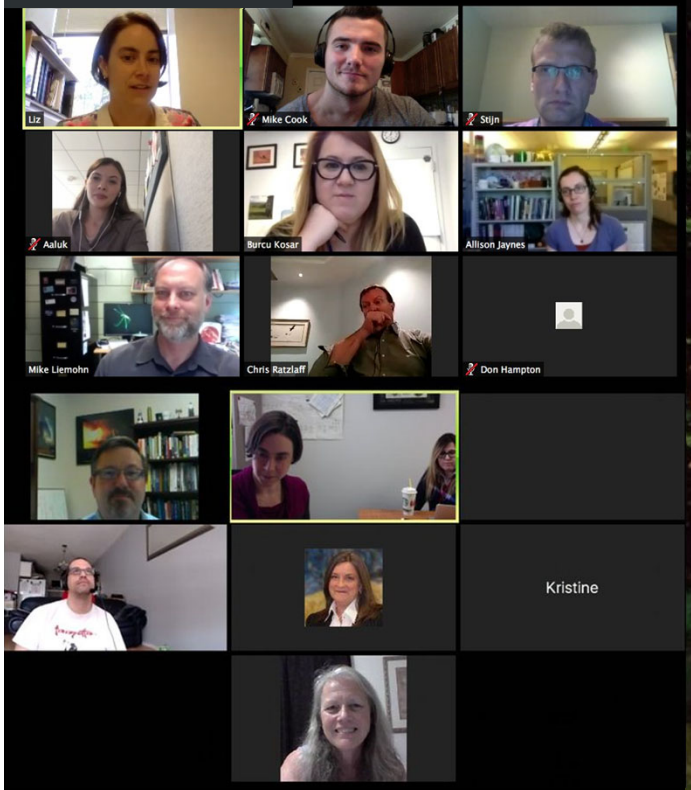
MACLEAN'S



MacDonald et al., Space Weather, 2015

The future is bright – join us!

- Next solar max with new cell phones
- Renewed interest in satellite auroral imaging
- NASA encouraging citizen science @DoNASAScience
- Postdoc opportunity



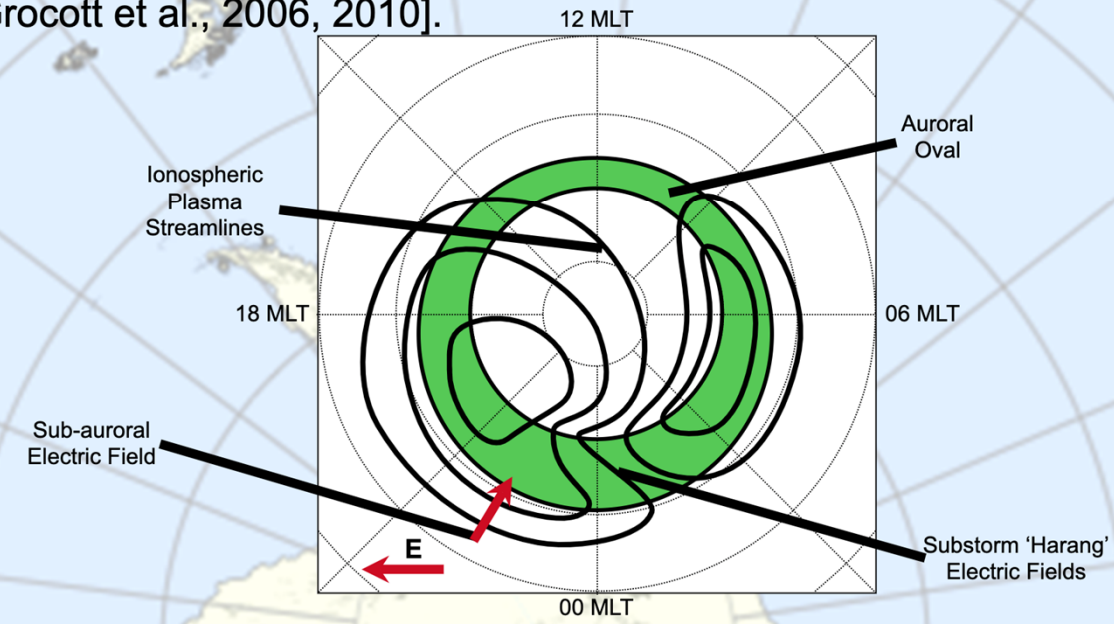
Ambassadors

Samsung Note 8, Feb 2020

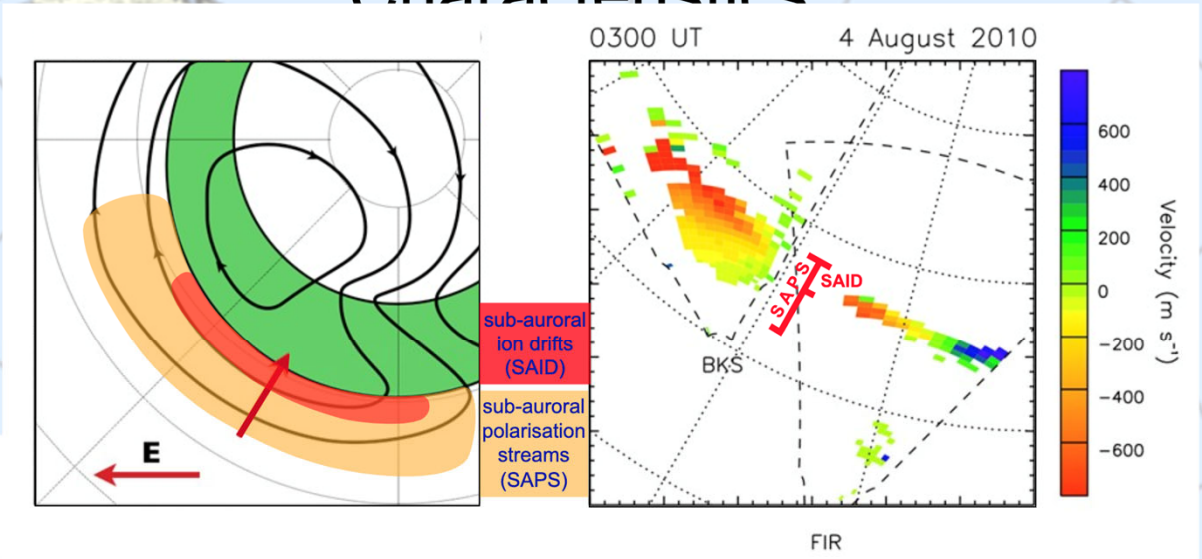
backup

Polar Cap and Auroral Convection

- During magnetospheric substorms, processes in the inner magnetosphere drive sub-auroral electric fields which couple to the auroral zones adding to the complexity of the electrodynamics [e.g. Grocott et al., 2006, 2010].



Observations: Flow Channel Characteristics



- Comparing the FIR data with BKS data reveals a similar fast flow region at similar latitudes in both hemispheres.
- BKS observed a wider band of scatter, illustrating that the high speed, narrow flow channel is embedded within a wider, slower band of flow.
- This is consistent with previous studies of sub-auroral ion drifts (SAID) [Spiro et al., 1979] and sub-auroral polarisation streams (SAPS) [Foster and Burke, 2002].

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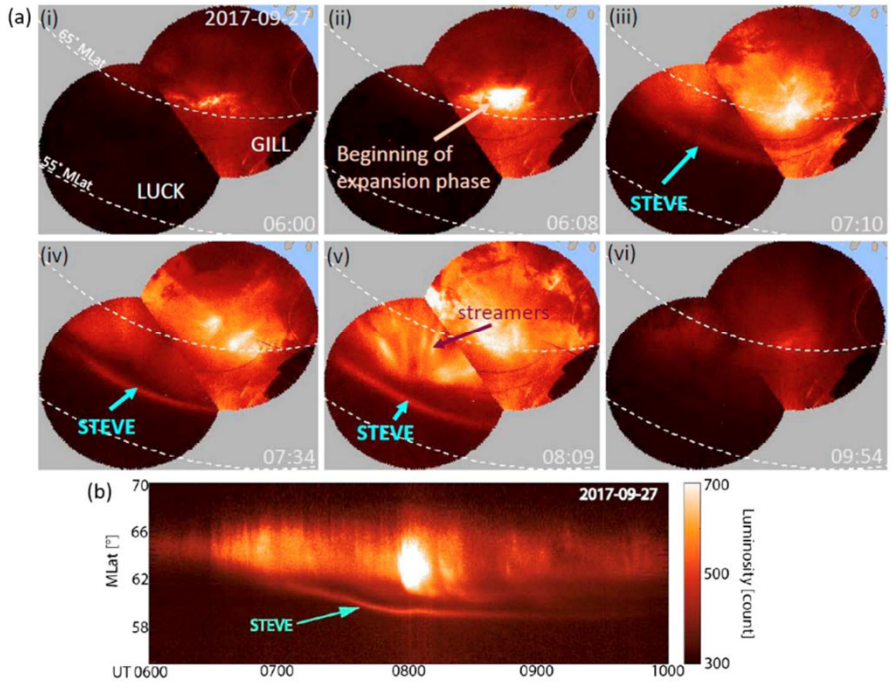

Figure 2. Example of a STEVE (Strong Thermal Emission Velocity Enhancement) event observed using Redline Emission Geospace Observatory (REGO) on 2017 September 27. (a) Temporal evolution of STEVE observed at Lucky Lake (LUCK). Gillam (GILL) all-sky imager provides data at higher latitudes. (b) LUCK keogram summarizing the event.

Gallardo-Lacourt et al., 2018