Solar Drivers of Space Weather

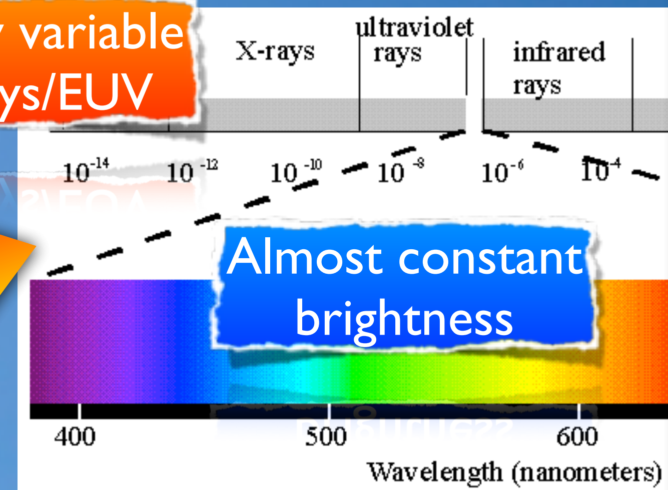
Mark Cheung (cheung@lmsal.com, @markcheung)
Lockheed Martin Solar & Astrophysics Laboratory, Palo Alto, CA, USA &
Stanford University, CA, USA

Bureau of Meteorology - Space Weather Users Workshop, Sydney, Nov 16th-17th 2017

What the Sun sends our way

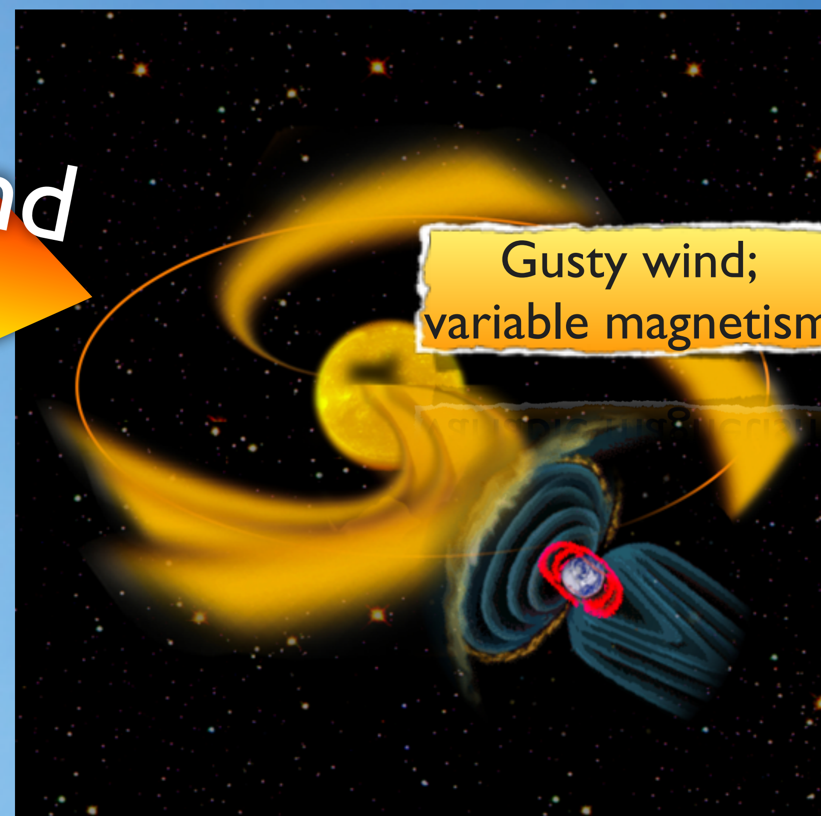
Light (X-ray to radio)

Highly variable X-rays/EUV



Almost constant brightness

Magnetized wind



Gusty wind; variable magnetism

Particle radiation

Highly variable particle streams

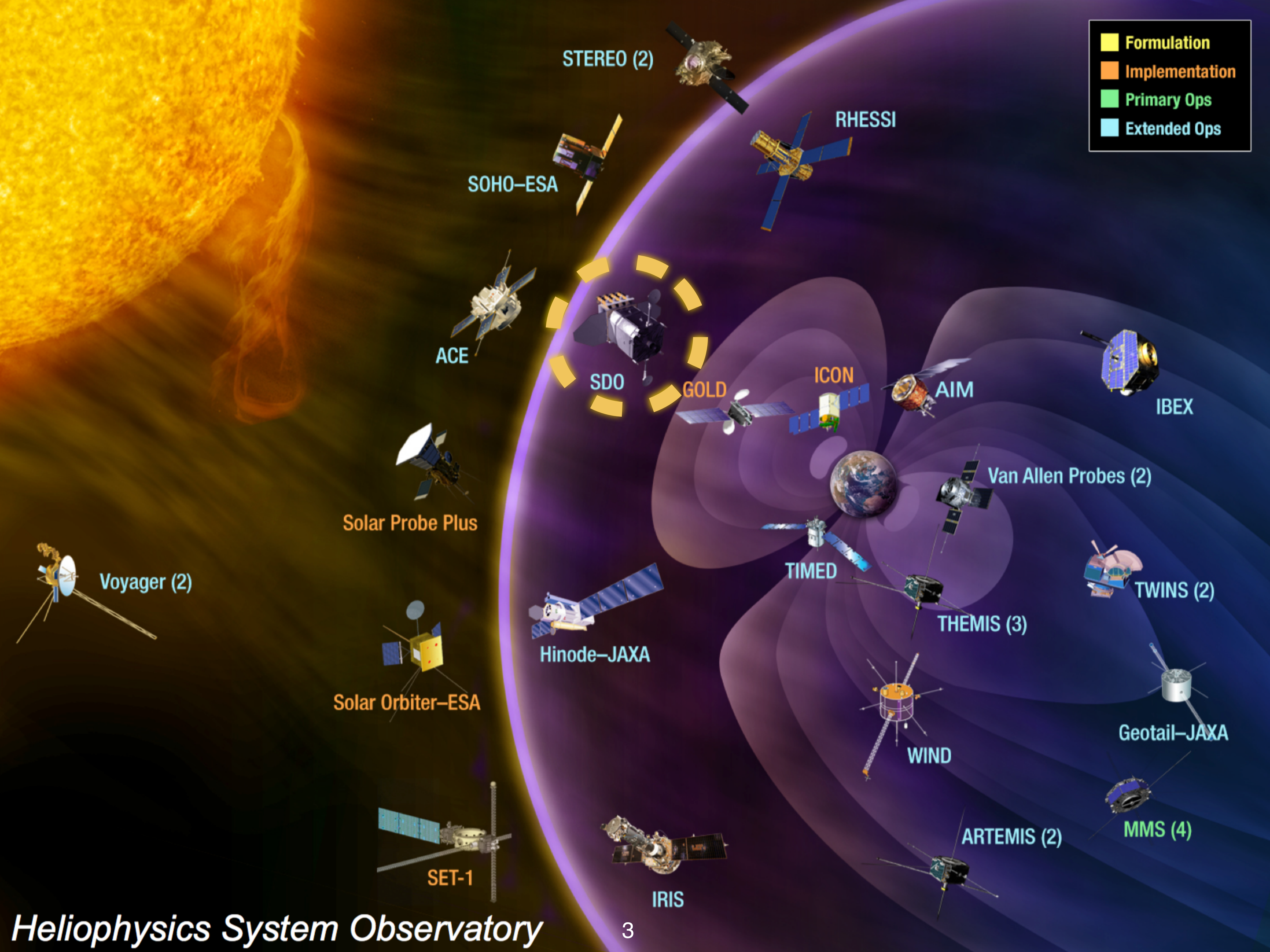
Slide courtesy: Schrijver et al. (COSPAR/ILWS Space Weather Roadmap)

Examples of space weather phenomena:

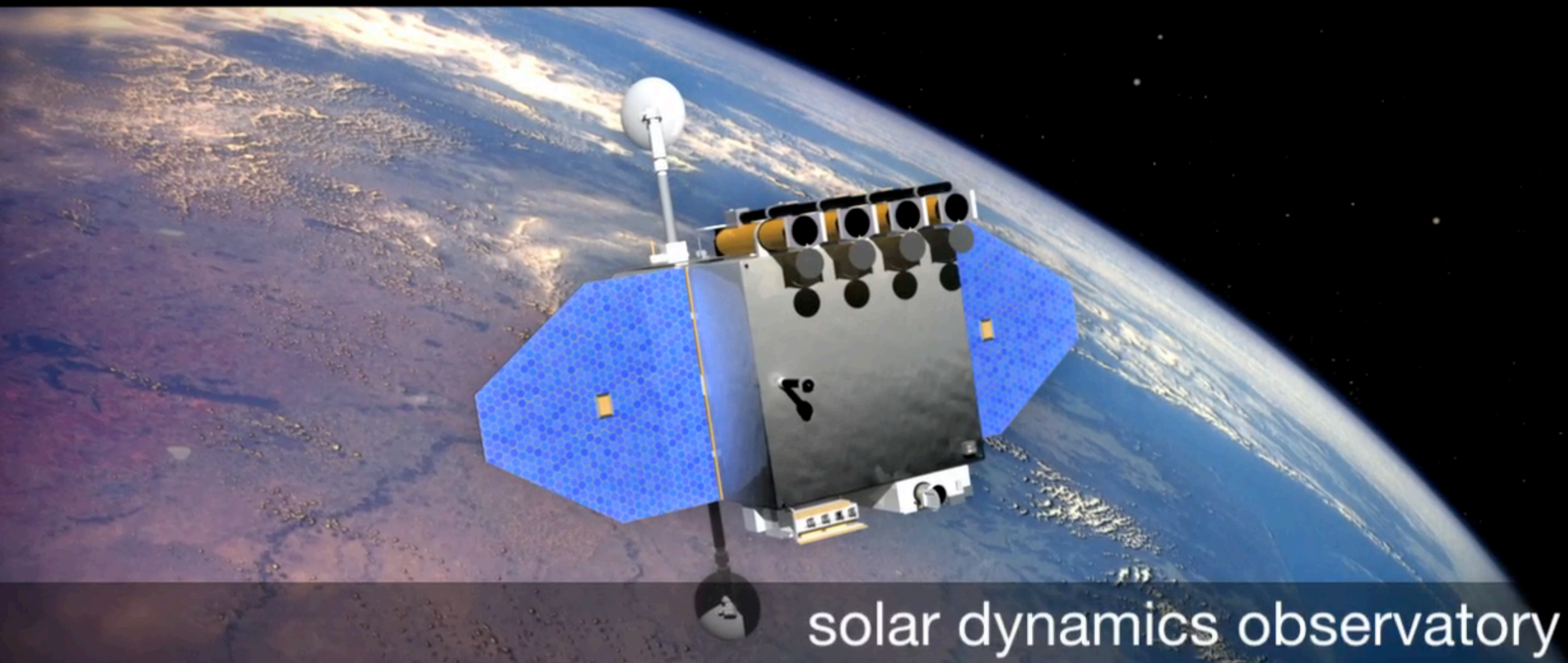
Geomagnetic storms: couple into power grids, cause ionospheric disturbances affecting satellite-based navigation. Aurorae

Radiation storms: hazard to astronaut health and satellite function; affects high-latitude radio comm.; position errors on navigation.

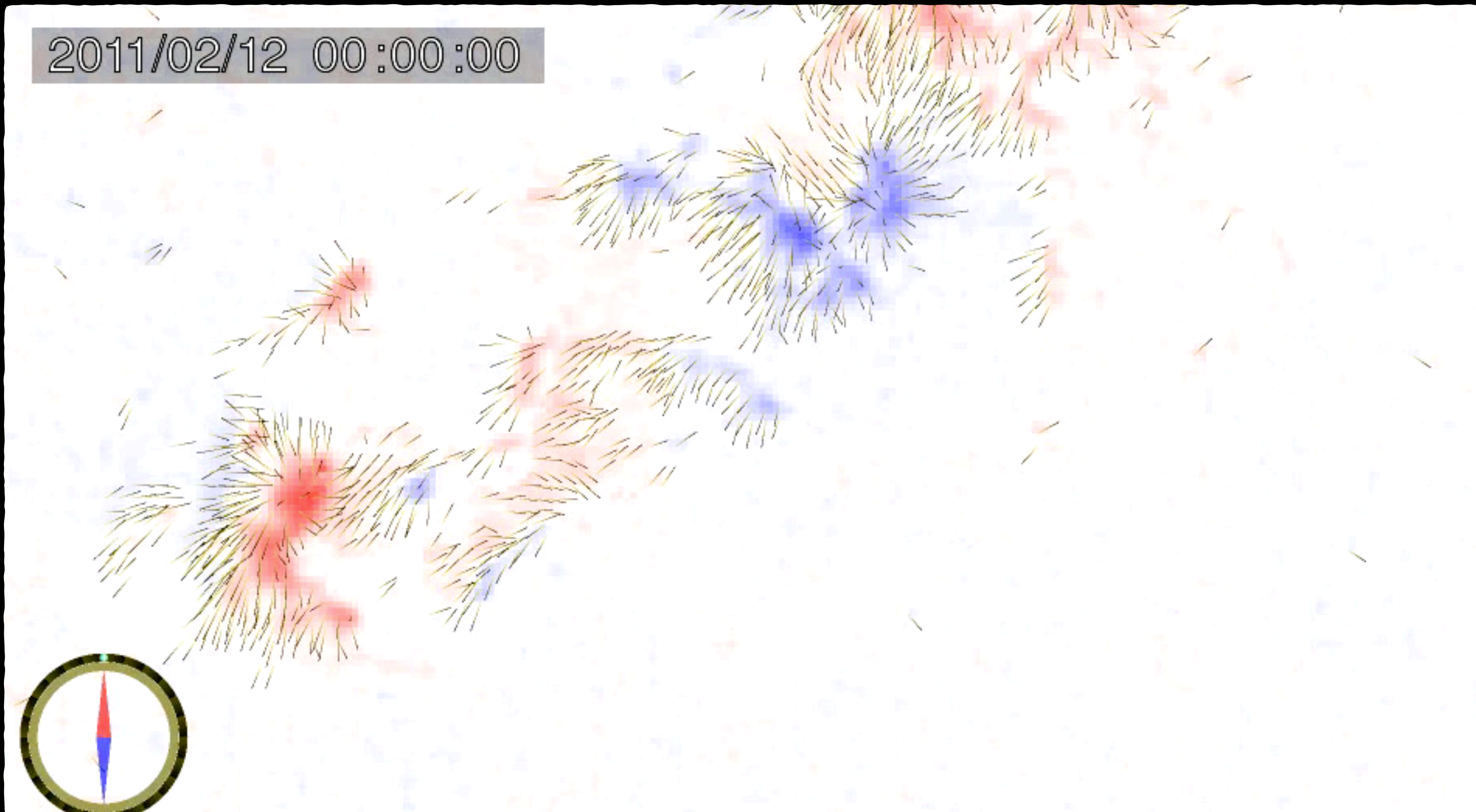
Radio blackouts. Satellite drag affecting orbits and re-entry.


Formulation
Implementation
Primary Ops
Extended Ops
STEREO (2)
RHESSI
SOHO–ESA
ACE
SDO
GOLD
ICON
AIM
IBEX
Solar Probe Plus
Van Allen Probes (2)
TIMED
Voyager (2)
TWINS (2)
THEMIS (3)
Hinode–JAXA
Solar Orbiter–ESA
Geotail–JAXA
WIND
MMS (4)
ARTEMIS (2)
SET-1
IRIS
Heliophysics System Observatory

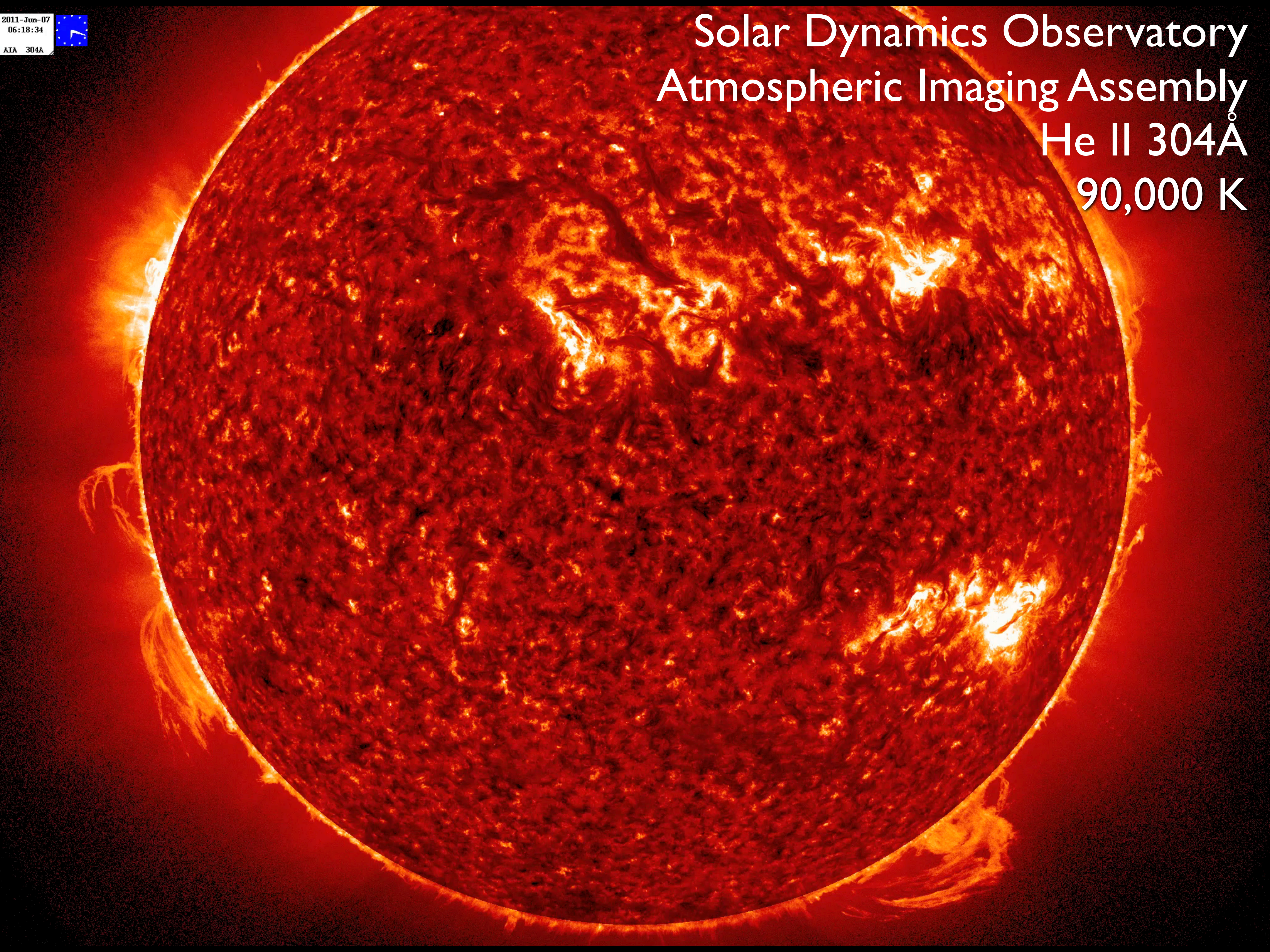
Launched in 2010, SDO's main goal is to understand, *driving toward a predictive capability*, those solar variations that influence life on Earth and humanity's technological systems.



SDO images the sun's surface, atmosphere and interior.
The mission generates about 3 terabytes worth of science data everyday.
For NASA Heliophysics, SDO *is* Big Data.

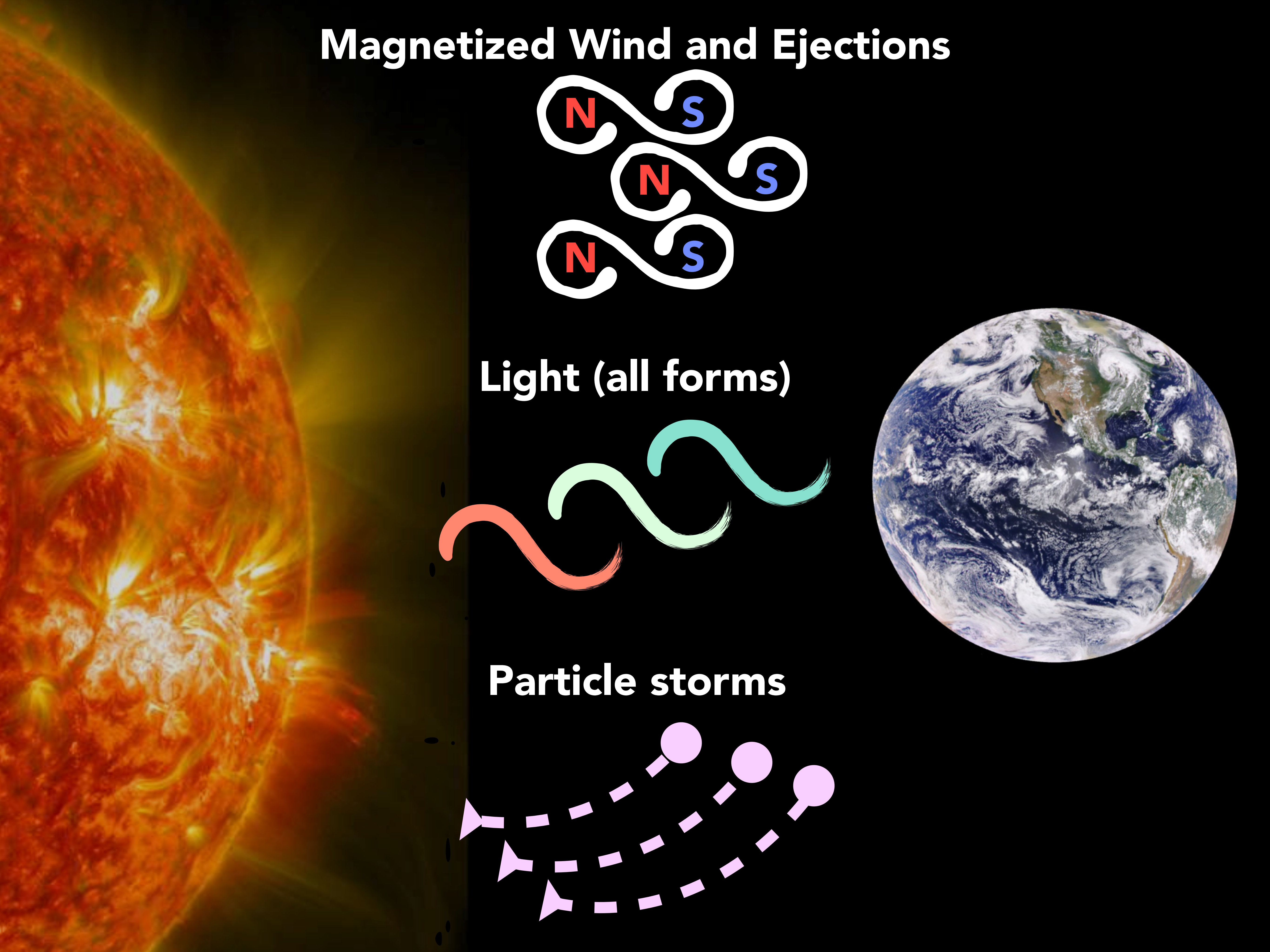


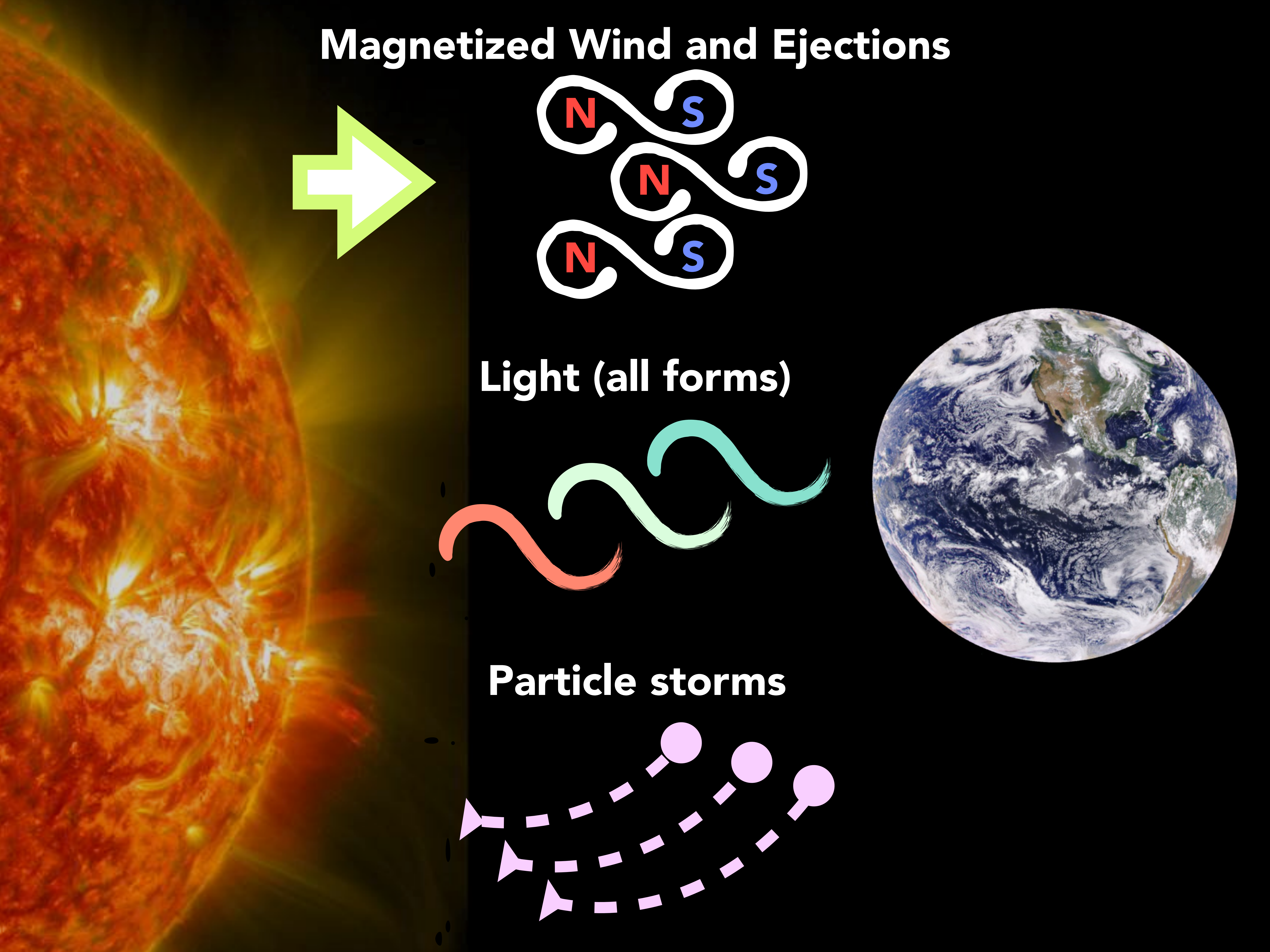
SDO/HMI vector magnetogram sequence of NOAA AR 11158
Credit: Keiji Hayashi (HMI)


2011-Jun-07
06:18:34
AIA 304A
Solar Dynamics Observatory
Atmospheric Imaging Assembly
He II 304Å
90,000 K

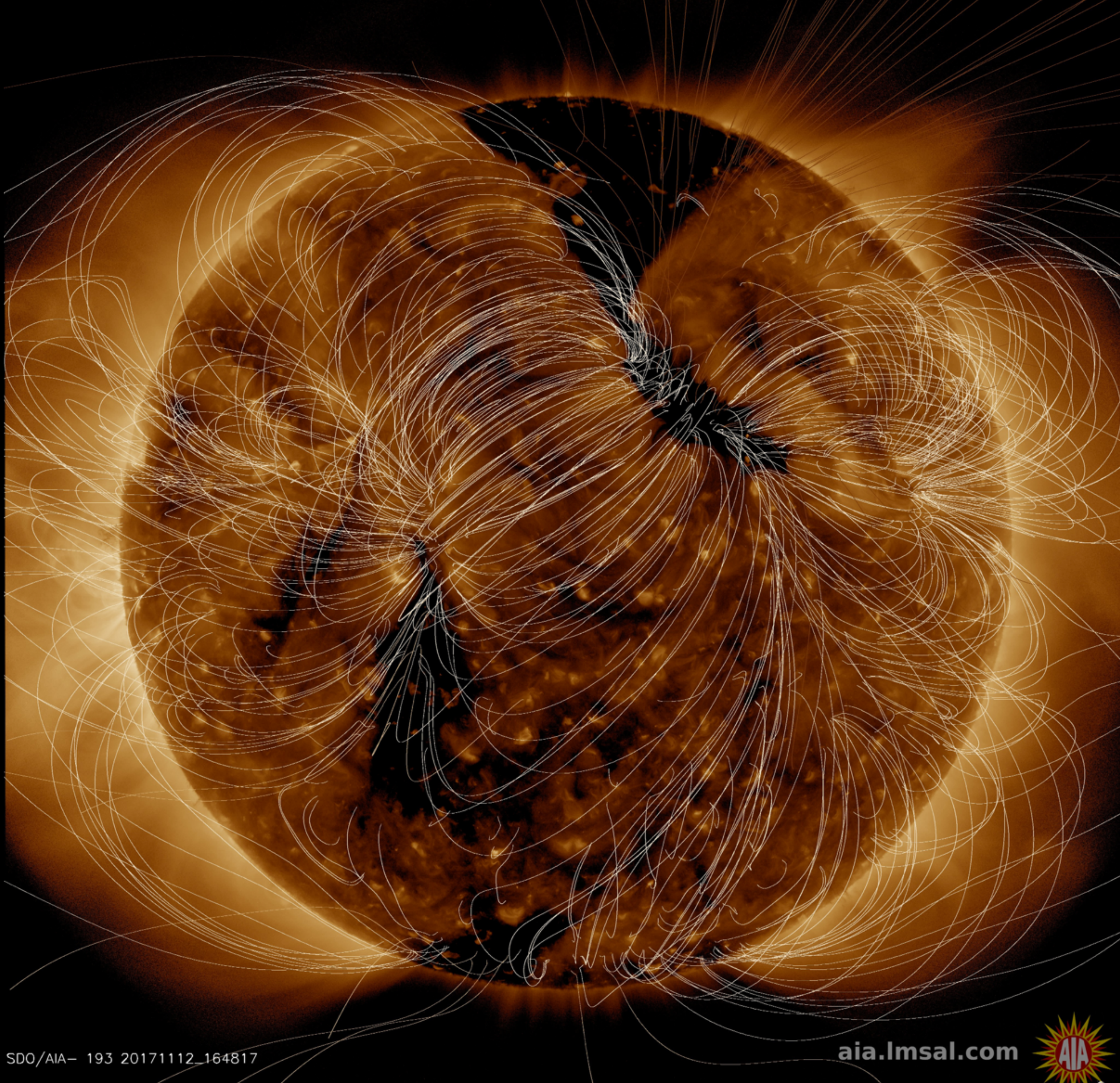
SDO in a Nutshell

- 3 instruments monitoring the Sun all the time since May 2010
  - Atmospheric Imaging Assembly (PI is Cheung@LMSAL): visible, UV, and EUV full disk images of the photosphere, chromosphere, transition region and corona at 4096x4096 pixels.
  - Helioseismic & Magnetic Imager (PI is Scherrer@Stanford): visible light full disk dopplergrams and magnetograms at 4096x4096 pixels.
  - EUV Variability Experiment (PI is Woods@LASP, CU Boulder): disk-integrated EUV irradiance spectra at 1 Å resolution.
- About 12 PBs of data to date.
- SDO science data has been part of over 3000 refereed publications (18 in Science, 17 in Nature, 46 PhD dissertations).
- Easy data access: First authors are spread out over 33 countries with co-authors from at least another 18 (source: NASA/ADS).


Magnetized Wind and Ejections
N
S
N
S
N
S
Light (all forms)
Particle storms


Magnetized Wind and Ejections
N
S
N
S
N
S
Light (all forms)
Particle storms

Coronal Holes and the Solar Wind



Arge & Pizzo (2000):
Use expansion factors of coronal hole fields to set a solar wind speed at the source surface ("base" of the source of the solar wind).

Left: Magnetic field lines from a potential field source surface (PFSS) extrapolation overloaded on AIA 193 Å image.

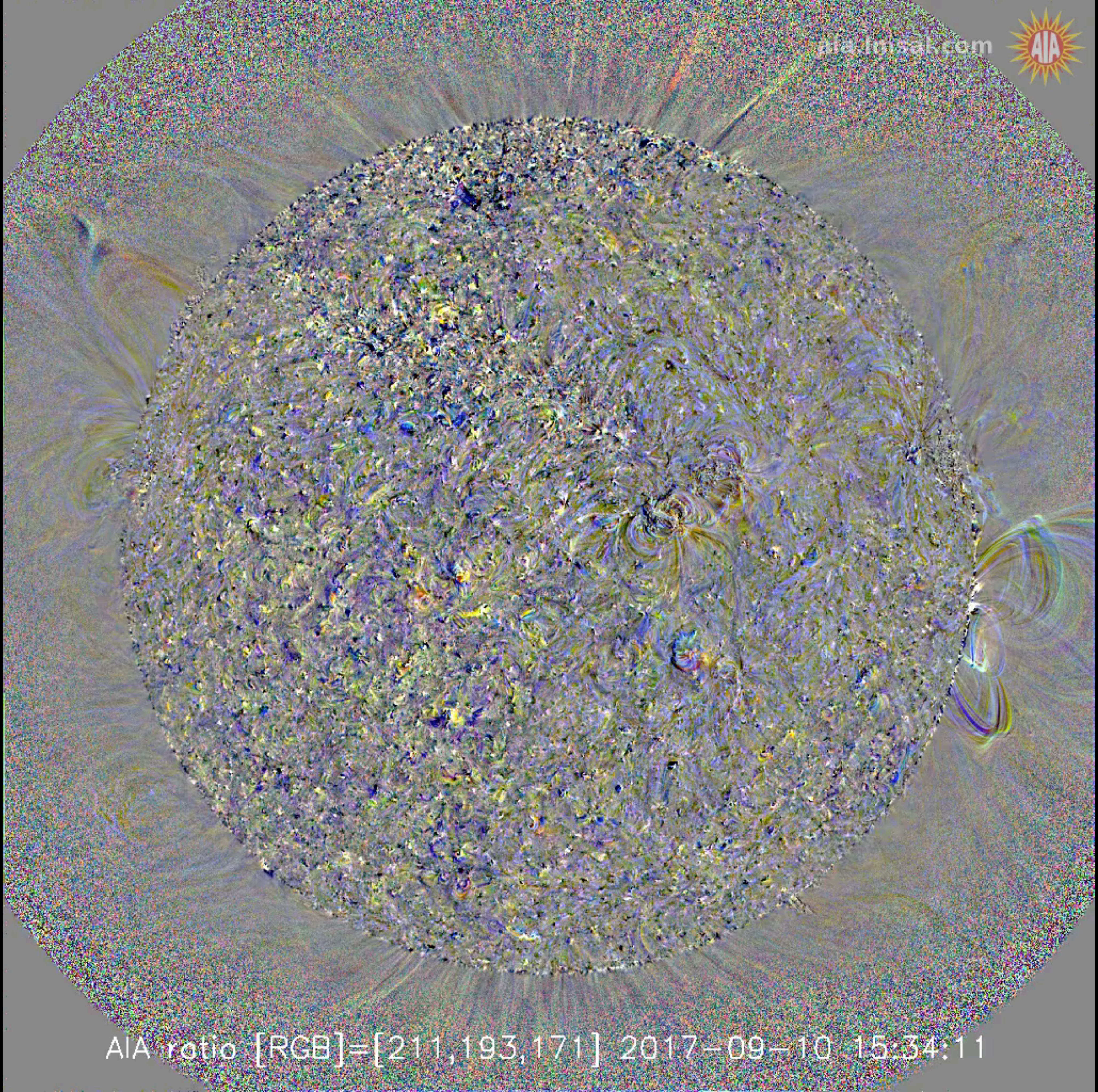
NOAA's Space Weather Prediction Center uses a solar wind (WSA-ENLIL) model based on magnetograms from ground-based observatories (Wilcox or GONG). Some research models uses SDO/HMI magnetograms and/or AIA coronal holes for solar wind predictions.

Miloslav Druckmüller Image + Predicted pB

Courtesy Z. Mikić (PSI) & Druckmüller

Meng
Jin

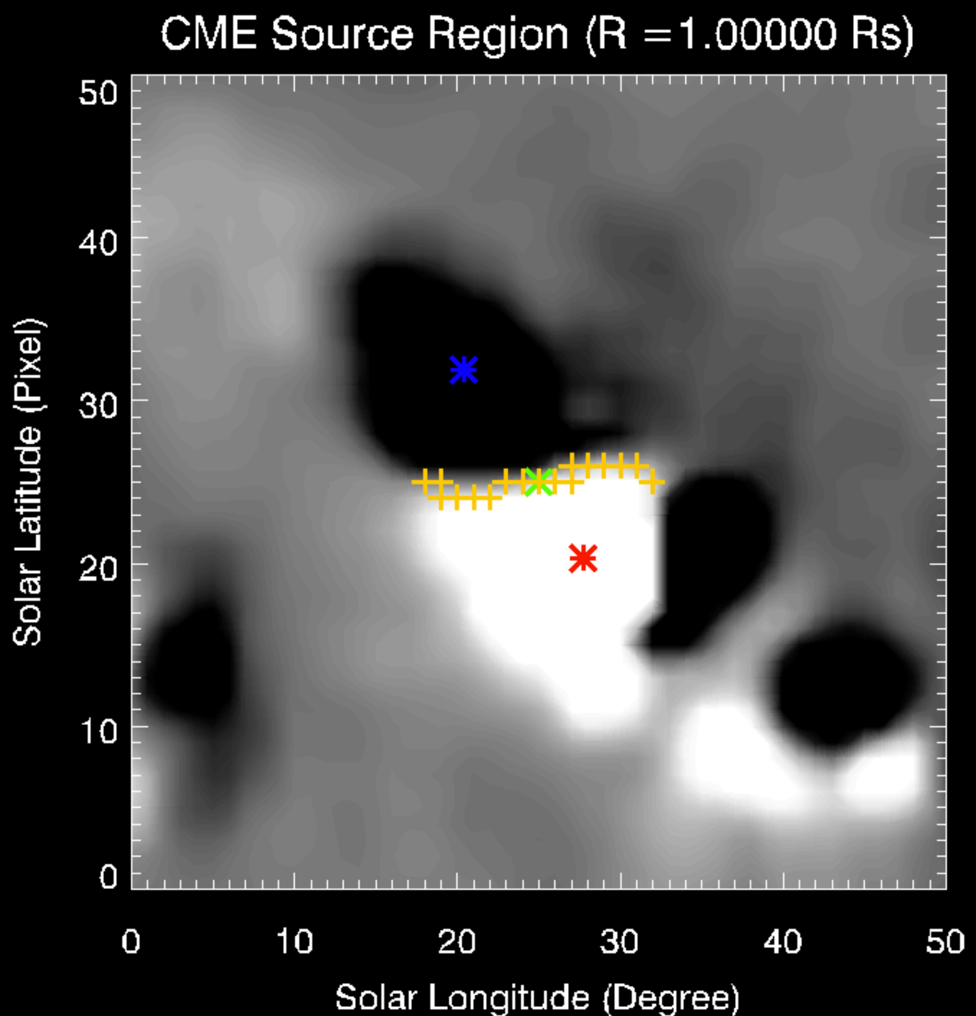
2017 September 10th X8.2



Flare + Global EUV wave

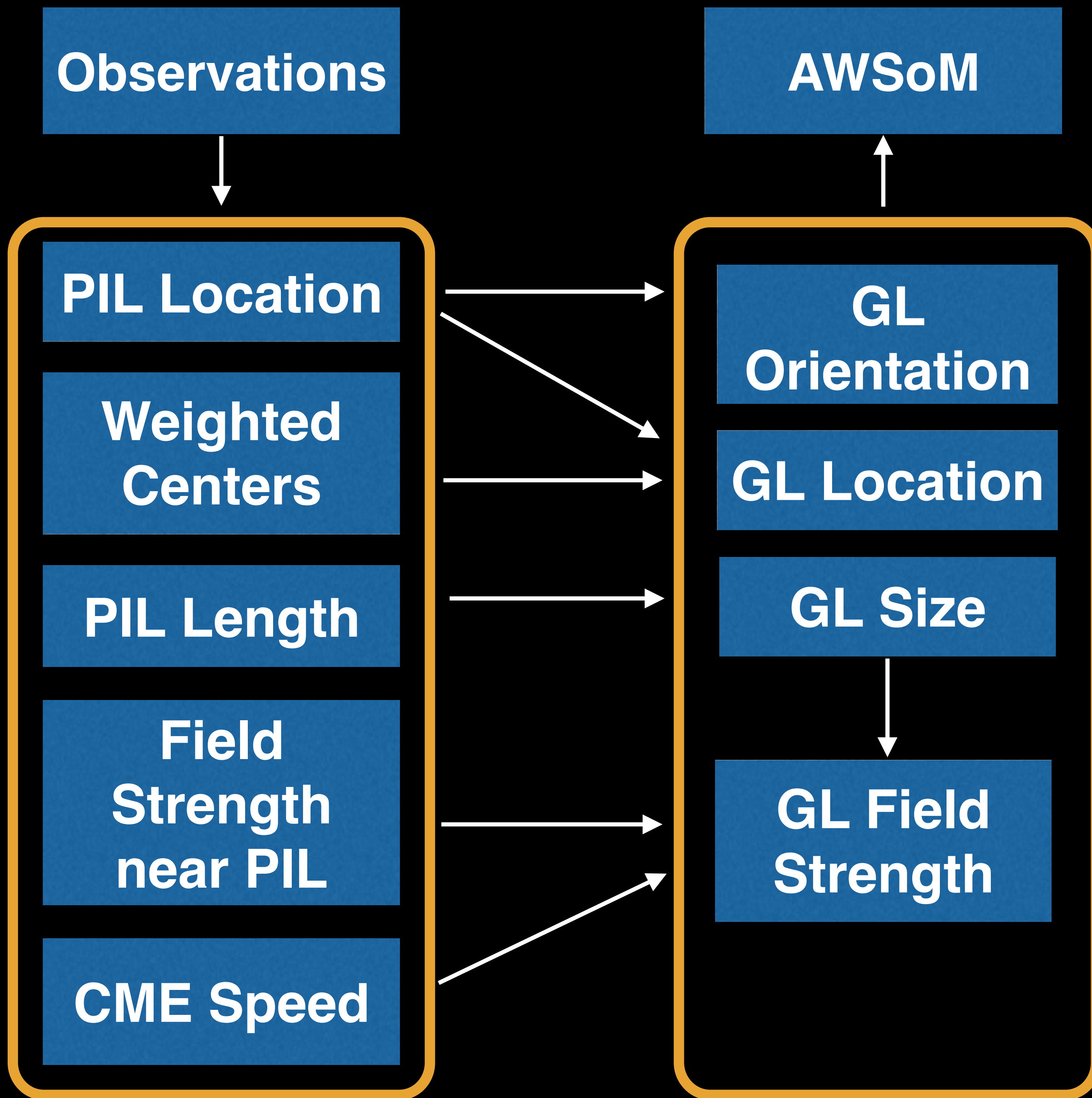
EEGGL: Eruptive Event Generator (Gibson and Low)

AR 11164



Weighted Centers
Polarity Inversion Line (PIL)
GL Flux Rope Location

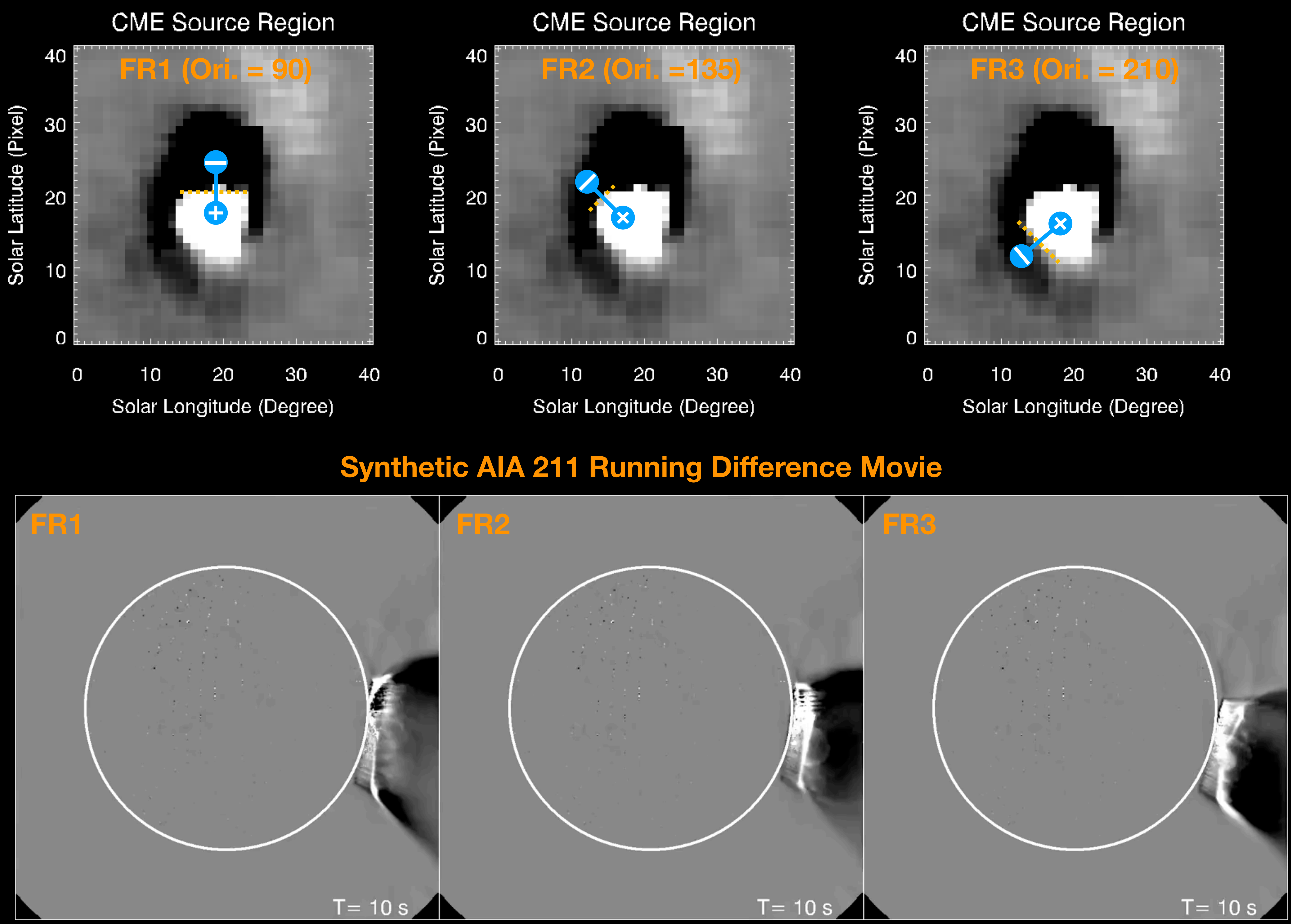
AWSoM: Alfvén Wave Solar Model
(*van der Holst et al. 2014*)

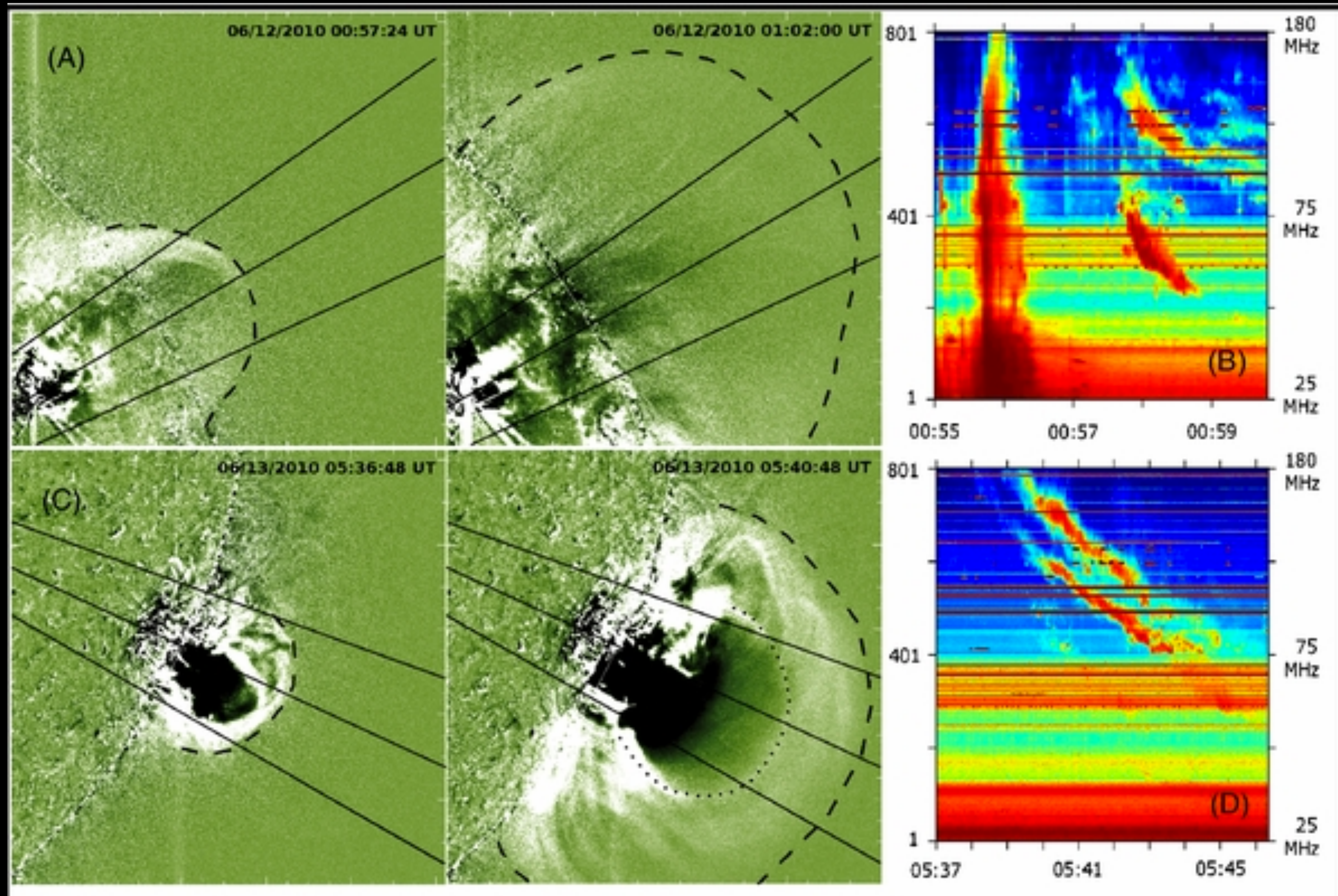


(Jin et al. 2017)

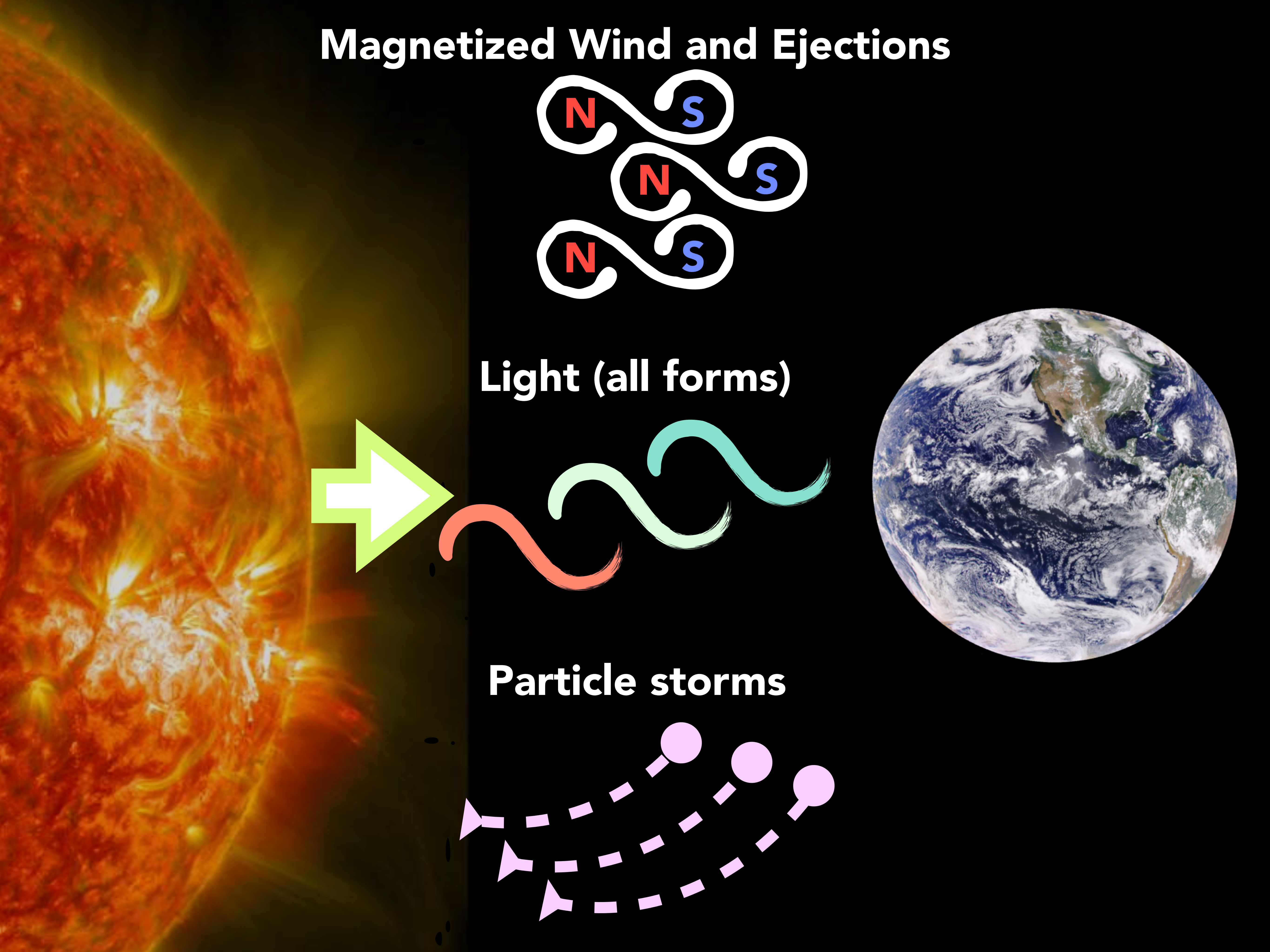
More information: https://ccmc.gsfc.nasa.gov/eeggl/

- **For this study, we utilize a global magnetic map sampled from an evolving photospheric flux transport model (*Schrijver &DeRosa 2003*), which uses HMI magnetograms as an input.**


CME Source Region
FR1 (Ori. = 90)
FR2 (Ori. =135)
FR3 (Ori. = 210)
Solar Latitude (Pixel)
Solar Longitude (Degree)
0
10
20
30
40
Synthetic AIA 211 Running Difference Movie
FR1
FR2
FR3
T= 10 s

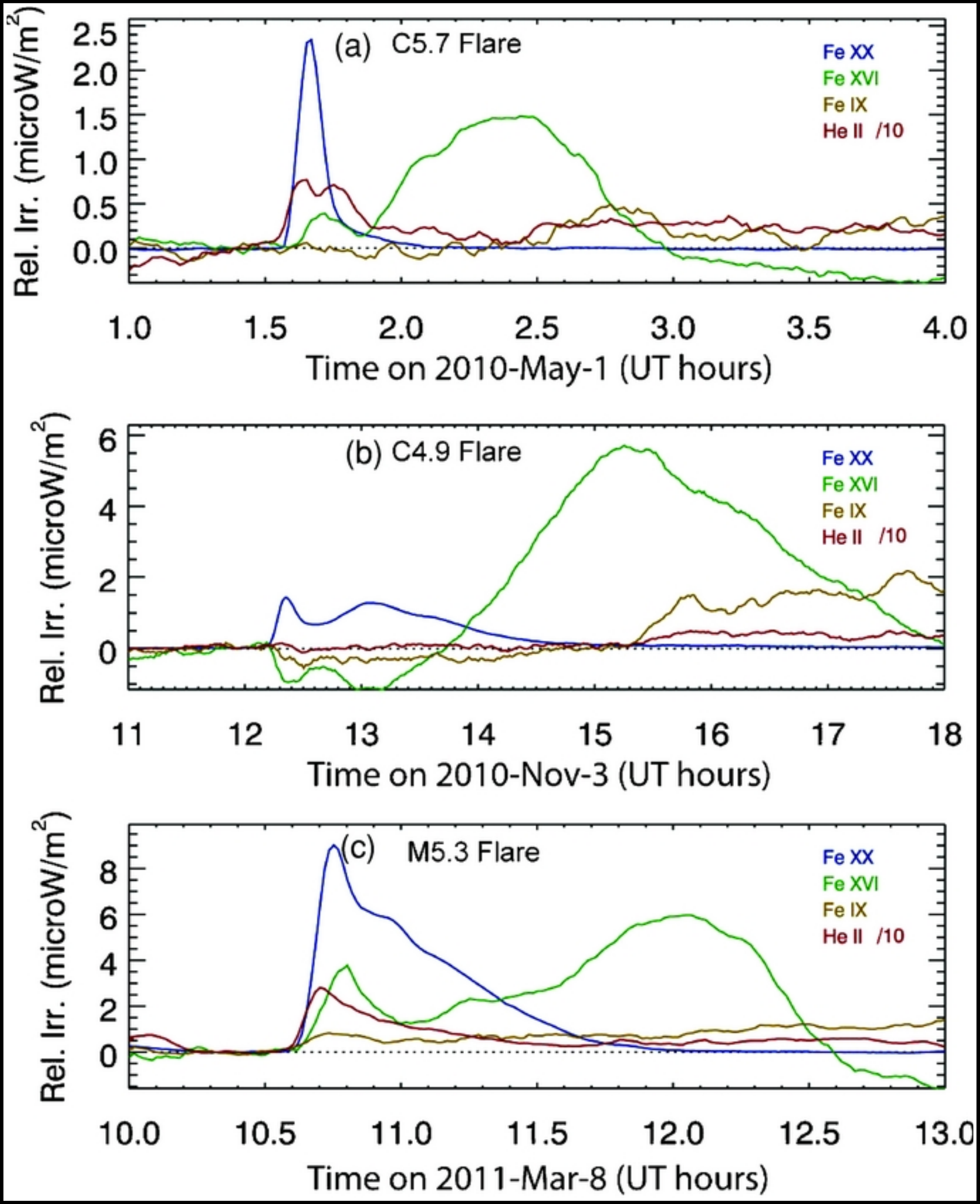


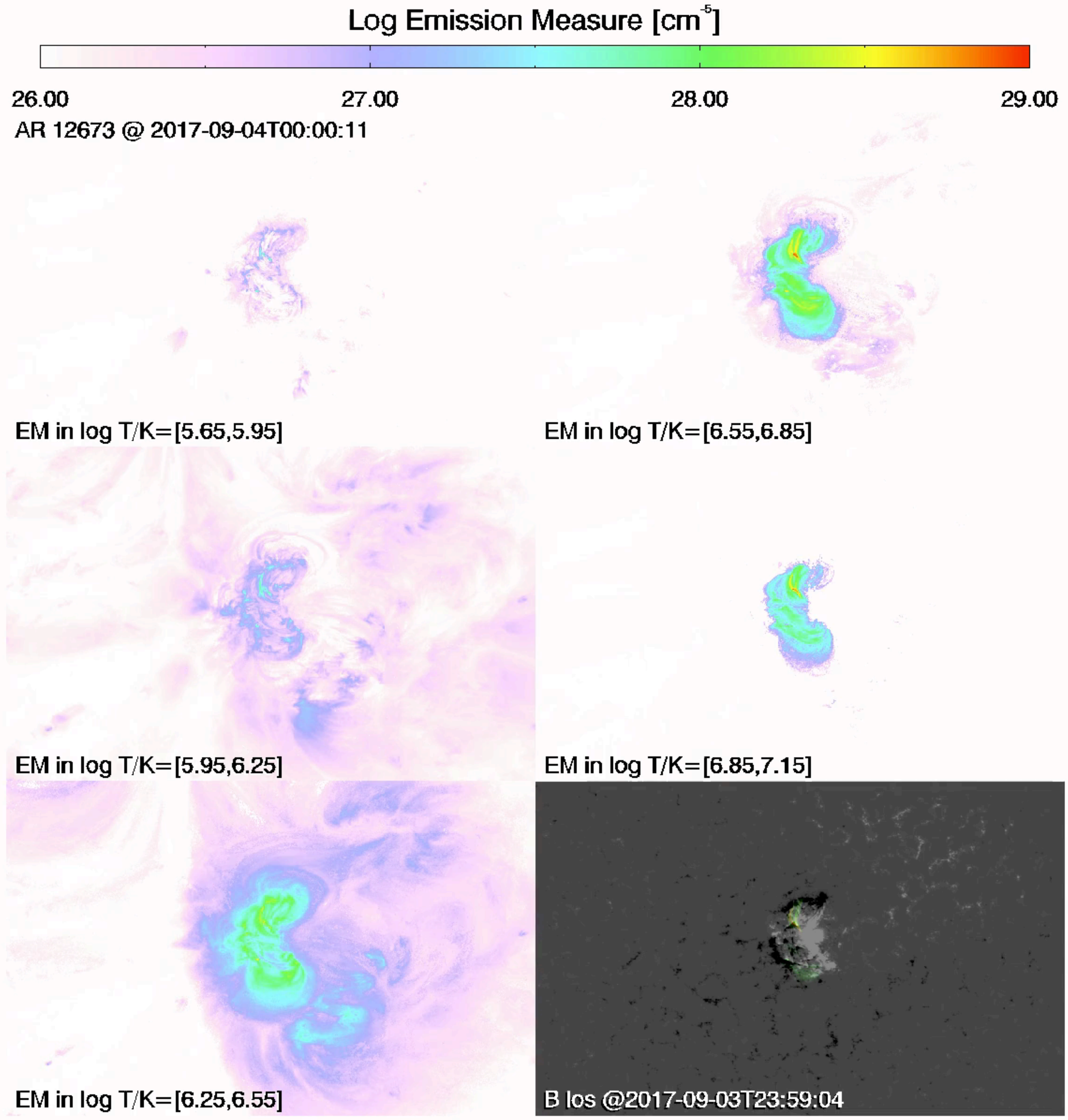
- Kozarev et al. (2011): Spatiotemporal correspondence between EUV shock waves (seen in AIA) and type II radio bursts. Characterization of density jumps, and suggestion that magnetic geometry plays an important role in effectiveness of particle acceleration.
- <u>Schmidt, Cairns & Lobzin (2014, 2016, 2017):</u> Type II radio bursts and solar wind in-situ Bz measurements successfully modeled with CME simulations using the BATS-R-US MHD code.


Magnetized Wind and Ejections
N
S
N
S
N
S
Light (all forms)
Particle storms

Woods et al. (2011): Flares

- During the impulsive phase, transition region (e.g. He II 304 Å) emission dominates EUV irradiance contributions.
- During the gradual phase, T>5 MK EUV coronal emission dominates, and is strongly correlated with GOES X-ray flux.
- During the late phase, warm (T~3 MK) EUV emission dominates. These come from a different set of flare loops.
- Implications for ionospheric models that use solar X-rays/EUV driving as input.





NOAA AR 12673 temperature maps (emission measure)

Other panels:

EM in various log T bins

Lower right panel only

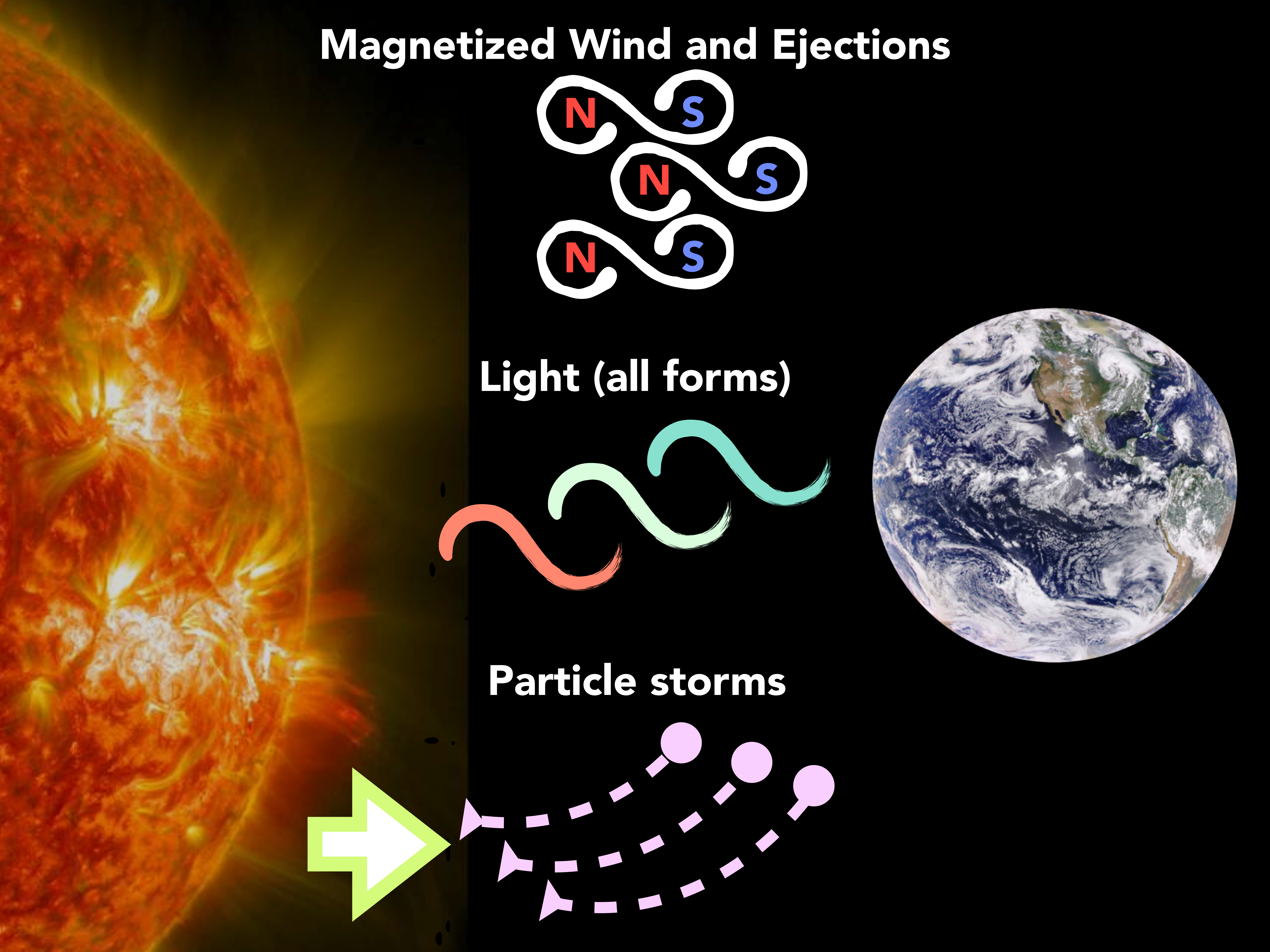
Greyscale: B_{los} from HMI

Green: 6MK EM

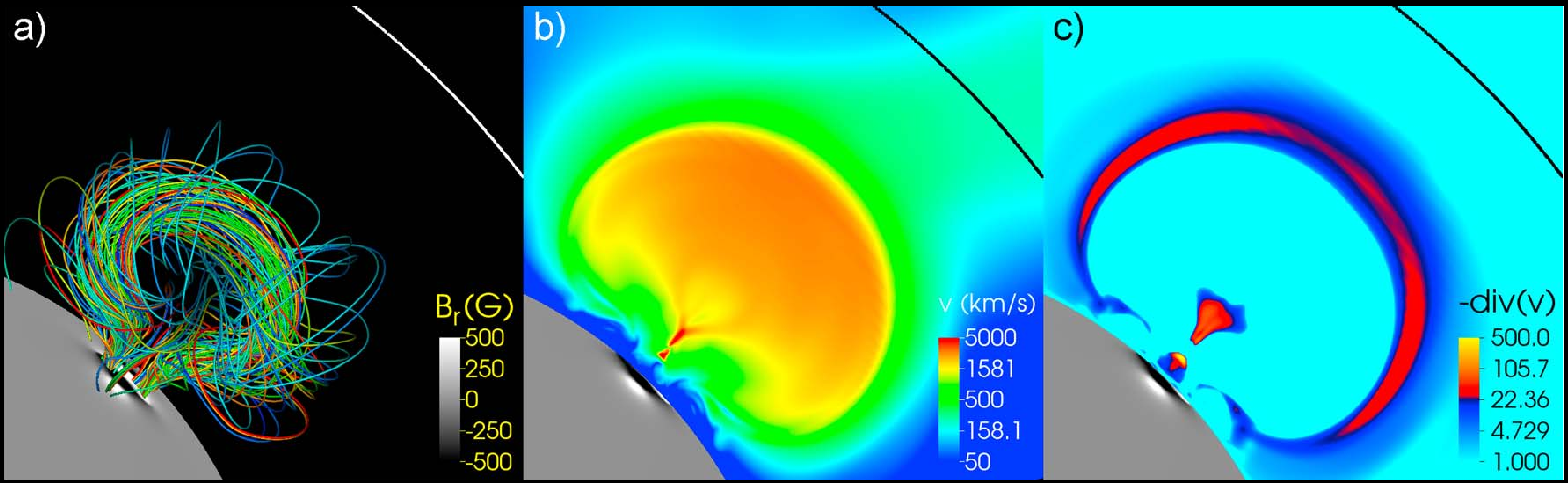
Yellow/Red: 10 MK EM

Upcoming SDO/AIA Webinars

- Topic: Thermal Diagnostics with SDO/AIA
- Webinar Duration: ~90 to 120 minutes
- Option 1: Nov 30th 2017, Washington DC @ 23:00, Beijing @ 12:00, Tokyo @ 13:00, London @ 04:00, Frankfurt @ 05:00
- Option 2: Dec 1st 2017, Washington DC @ 10:00, Beijing @ 23:00, Tokyo @ 00:00 (Fri Dec 2nd), London @ 15:00, Frankfurt @ 16:00
- Find registration link in the Nov 1st issue of SolarNews http://solarnews.nso.edu


Magnetized Wind and Ejections
N
S
N
S
N
S
Light (all forms)
Particle storms

Coronal Mass Ejections (CMEs)

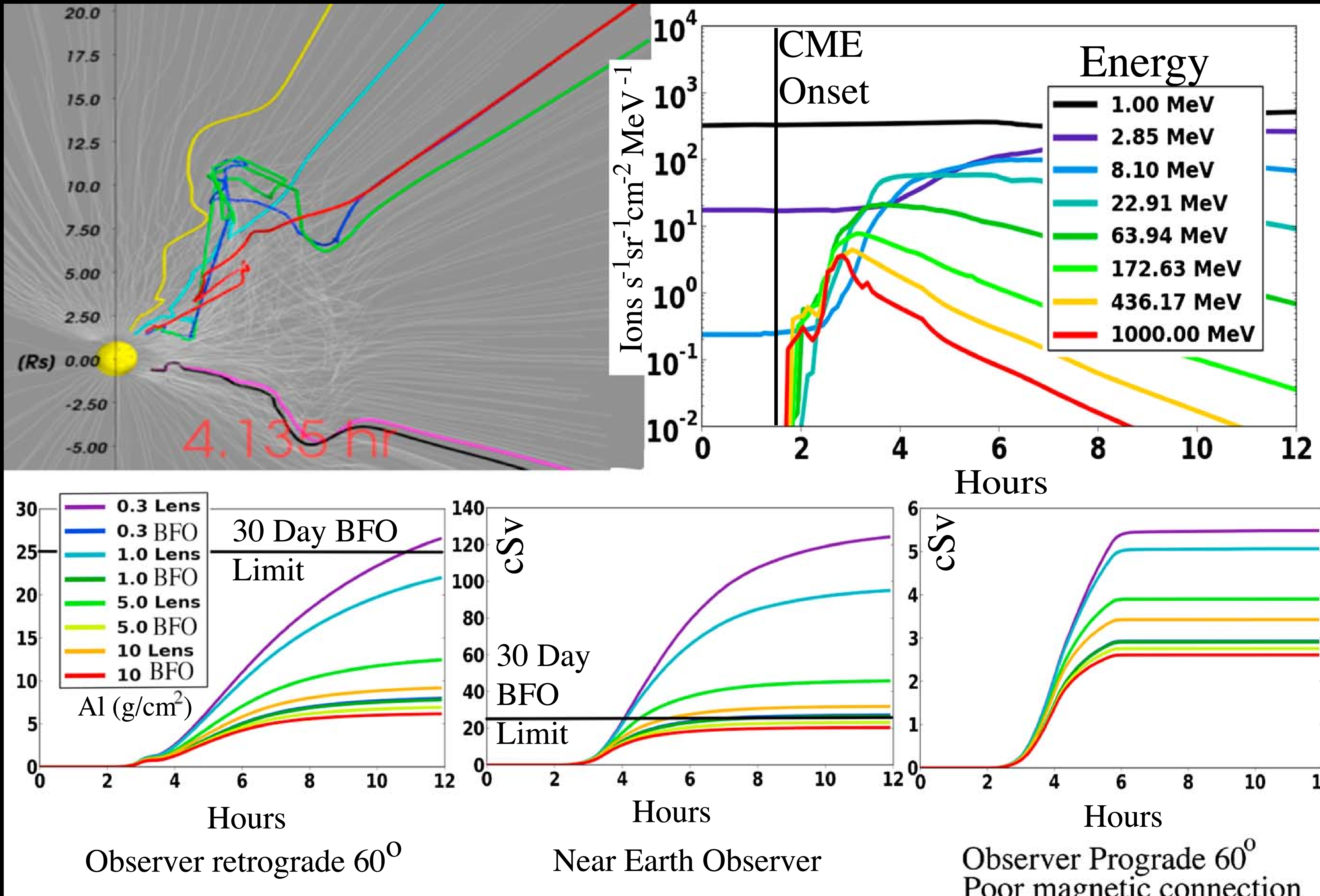


Magnetic flux rope   Radial velocity (km/s)   Compression rate

During the initiation and propagation of a CME, particles can undergo diffusive shock acceleration across the CME-driven shock.

Schwadron et al. (2014, *Space Weather*, 12, 323-328)

Solar Energetic Particles (SEPs)



Schwadron et al. (2014, *Space Weather*, 12, 323-328)

Research to Operations to Research

- SDO is a science mission with an operations bent.
  - Continuous, nominal observing program (very rarely, campaigns)
- SDO as a research mission:
  - Unique data products (vector magnetograms, EUV images with wide thermal coverage, spectral irradiance, helioseismology)
  - Anchor for observations of other HSO assets
- SDO as an "operations" facility:
  - Dedicated ground system with dual antennae
  - Low latency, near-real time data processing
  - Well-documented Application Programming Interfaces (APIs)
  - World-wide data distribution network
- Scientific aspirations need not be the enemy of operational requirements.
- Operational Space Weather agencies piggybacking on SDO data: fantastic!
- But… please don't take SDO for granted.

OPEN
DATA
POLICY

APPLICATION
PROGRAMMING
INTERFACES

COLLABORATIVE
METADATA
ENVIRONMENT

In plain English, more than just ftp sites and HTML forms.

Advances in Space Research

Volume 55, Issue 12, 15 June 2015, Pages 2745-2807

Understanding space weather to shield society: A global road map for 2015–2025 commissioned by COSPAR and ILWS

Carolus J. Schrijver [a], Kirsti Kauristie [b], Alan D. Aylward [c], Clezio M. Denardini [d], Sarah E. Gibson [e], Alexi Glover [f], Nat Gopalswamy [g], Manuel Grande [h], Mike Hapgood [i], Daniel Heynderickx [j], Norbert Jakowski [k], Vladimir V. Kalegaev [l], Giovanni Lapenta [m], Jon A. Linker [n], Siqing Liu [o], Cristina H. Mandrini [p], Ian R. Mann [q], Tsutomu Nagatsuma [r], Dibyendu Nandy [s], Takahiro Obara [t], T. Paul O'Brien [u], Terrance Onsager [v], Hermann J. Opgenoorth [w], Michael Terkildsen [x], Cesar E. Valladares [y], Nicole Vilmer [z]

[x]Space Weather Services, Bureau of Meteorology, Surry Hills NSW, Australia

Pathway I recommendations: to obtain forecasts more than 12 h ahead of the magnetic structure of incoming coronal mass ejections and their impact in geospace to improve alerts for geomagnetic disturbances and strong GICs, related ionospheric variability, and geospace energetic particles:

Maintain existing essential capabilities:

- solar magnetic maps (GBO, SDO) and EUV/X-ray images at arcsec and few-second res. (SDO; Hinode), and solar spectral irradiance observations;
- solar coronagraphy, best from multiple perspectives (Earth's view and L1: GBO and SoHO; and well off Sun–Earth line: STEREO);
- in-situ measurements of solar-wind plasma and magnetic field at, or upstream of, Sun–Earth L1 (ACE, SoHO; DSCOVR);
- for several years, continue to measure the interaction across the bowshock-magnetopause (as now with Cluster/ARTEMIS/THEMIS; soon with MMS), to better understand wind-magnetosphere coupling;
- satellite measurements of magnetospheric magnetic and electric fields, plasma parameters, soft auroral and trapped energetic particle fluxes (e.g., Van-Allen Probes, LANL satellites, GOES, ELECTRO-L, POES, DMSP);
- ground-based sensors for solar, heliospheric, magnetospheric, and iono-/thermo-/mesospheric data to complement satellite data

DE GRUYTER Adv. Opt. Techn. 2014; 3(3): 309–314

Research Article Open Access

Stephen D. Gensemer* and David Farrant CSIRO

Fabrication and metrology of lithium niobate narrowband optical filters for the solar orbiter

Abstract: We report on the fabrication of custom voltage tunable etalons for the SO/PHI spaceborne solar imaging instrument [A. Gandorfer, S. K. Solanki, J. Woch, V. M. Pillet, A. A. Herrero, and T. Appourchaux, J. Phys.: Conference Series 271, 012086 (2011)]. The etalons were manufactured to place a transmission maximum within 0.3 Å of the FeI emission line at 6175.0 Å. Meeting this specification requires an overall thickness specified to within ±15 nm, over a 60 mm aperture. We describe here the metrology, modelling and coating procedures we developed to achieve this.

Keywords: electrooptic; etalon; Fabry-Perot; filter; lithium niobate; solar.

DOI 10.1515/aot-2014-0016
Received February 27, 2014; accepted February 27, 2014

1 Introduction

been a challenge for fabrication. Limitations in the thickness uniformity that is achievable by polishing have led to the development of vapour deposition as a method for correction of thickness nonuniformity, enabling us to produce substrates with thickness variations of <1 nm across 60 mm [4, 5]. Etalons made of lithium niobate ($LiNbO_3$) have the advantage of being tunable by tilting, temperature, and voltage. In addition, their high index of refraction allows them to be made thinner than comparable air-spaced etalons, resulting in low angular sensitivity. This makes them advantageous in telescopic systems, where a wide field of view is desired. Their light weight and stability also make them well suited to spaceborne instrumentation.

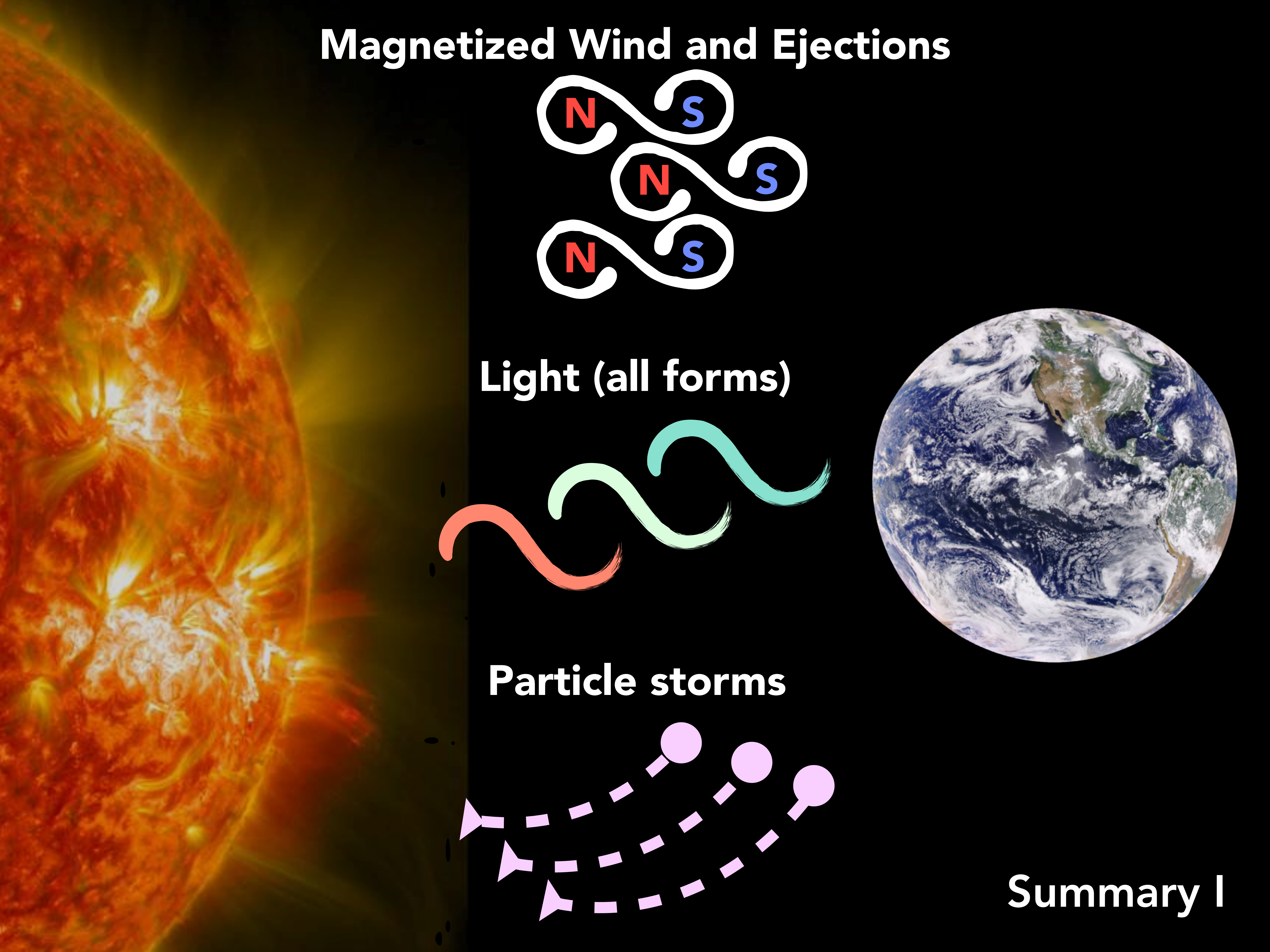
Typically $LiNbO_3$ voltage-tuneable etalons [6] are designed to be tuneable across the entire free spectral range, so that a fringe (transmission maximum) can be placed at any wavelength desired. The tuning range of such an etalon depends primarily on the thickness and the breakdown voltage, above which the crystal structure becomes depoled. The tuning range can be extended by varying the temperature and by tilting the etalon in addition to voltage tuning.

The CSIRO is world-renowned for their Fabry-Perot tunable filters.
Similar technology being considered for ESA's L5 mission concept

Model capability, archival research, or data infrastructure:

BoM x USyd

- near-real time, observation-driven 3D solar active-region models of the magnetic field to assess destabilization and to estimate energies;
- data-driven models for the global solar surface-coronal field;
- data-driven ensemble models for the magnetized solar wind;
- data assimilation techniques for the global ionosphere-magnetosphere-atmosphere system using ground and space data for nowcasts and near-term forecasts of geomagnetic and ionospheric variability, making optimal use of selected locations where laboratory-like test beds exist or can be efficiently developed;
- coordinated system-level research into large-scale rapid morphological changes in Earth's magnetotail and embedded energetic particle populations and their linkage to the ionosphere;
- system-level study of the mechanisms of the particle transport/acceleration/losses driving currents and pressure profiles in the inner magnetosphere;
- stimulate research to improve global geospace modeling beyond the MHD approximation (e.g., kinetic and hybrid approaches);
- develop the ability to use solar chromospheric and coronal polarimetry to guide full-Sun corona-to-heliosphere field models.


Magnetized Wind and Ejections
N
S
N
S
N
S
Light (all forms)
Particle storms
Summary I

Australia's potential contribution to international SpWx and SSA efforts: some bootstrapping examples

- Australian research is pushing forward the frontiers of SpWx research, e.g. data-constrained/data-driven modeling of CMEs.
- Australia has contributed to international coordination efforts by co-authoring the COSPAR Roadmap.
- BoM SWS products / services are used by Australia and overseas entities. Having APIs may help you show the world Australia's SSA program is forward looking (at minor cost).
- At the moment, Australia is reliant on data sources from foreign assets. However, Australia has unique technology to help maintain existing and develop new observational capabilities for SpWx prediction.

Contact: Mark Cheung (cheung@lmsal.com, @markcheung)

Summary II