Solar Wind, Space Weather and Solar-Terrestrial connection

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ESPM-17, September 2024

Space weather effects (SWx)

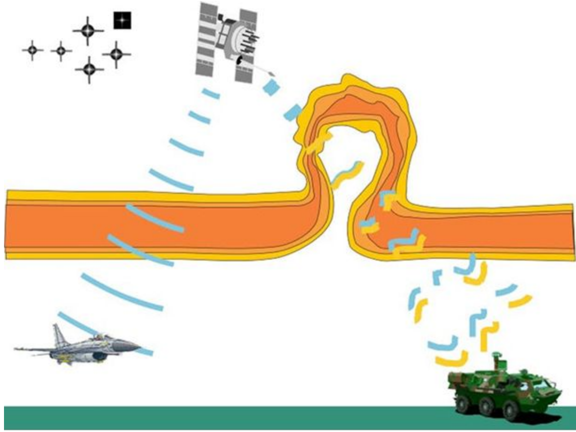
- NOAA recognises (and so do we):
  - **1. geomagnetic storms:** associated with solar wind disturbances
  - **2. radio blackouts:** associated with solar flares
  - **3. radiation storms:** associated with solar energetic particle (SEP) precipitation

- has been recognised ‘vital’ for security by multiple governments (US National Space Weather Strategy and Action Plan 2015, 2019, the UK Space Weather Preparedness Strategy 2015)

- power: non-catastrophic: **$5 - $10 bn/year**, catastrophic: **> $100 bn** [Eastwood et al. 2017]
- satellite operations: depending on the type of failure, **$1 - $100 m/mission** [Hapgood 2010]
- NSSC of CAS: a superstorm could cost trillions of dollars with **4 - 10 years** recovery time

1. Geomagnetic storms

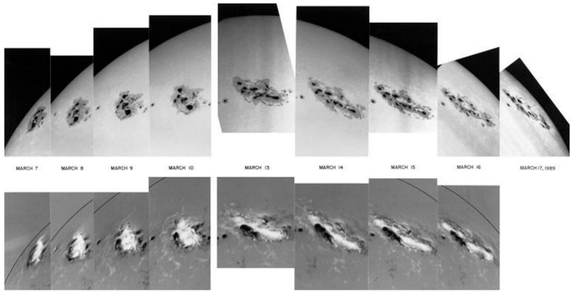
- **scintillation** post-midnight due to increased geomagnetic activity [Huang et al. 2005] at Takur Ghar in 2003 obstructed communication regarding an unsafe landing area
  - a Chinook helicopter crashed, seven people died



Credit: U.S. Air Force Research Laboratory (AFRL)
https://www.nasa.gov/mission_pages/cindi/five-years.html

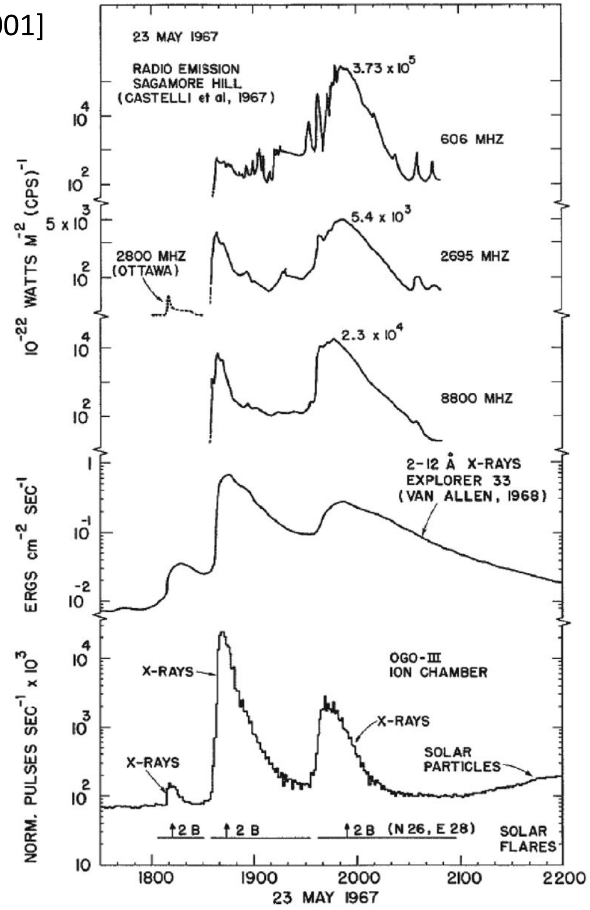
- Starlink lost 40 satellites on February 4, 2022 due to launching during a G1 storm that **increased atmospheric drag**
  - similarly, Skylab station planned for de-orbit in 1982, re-entered in 1979 because of higher solar activity

[Boteler 2019]



- **ground induced currents** from G5 caused a power network collapse in Quebéc on March 13, 1989; after 9 hours 17 % of the load still out of service, 6M people without electricity

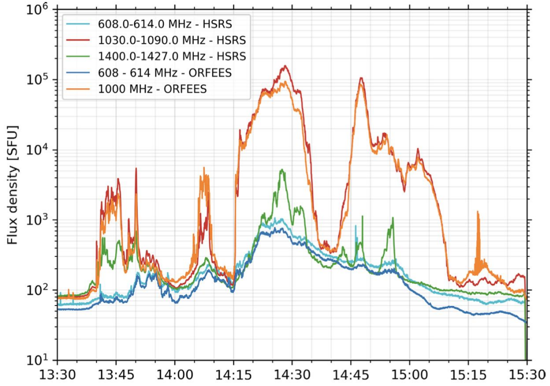
[Knipp et al. 2001]

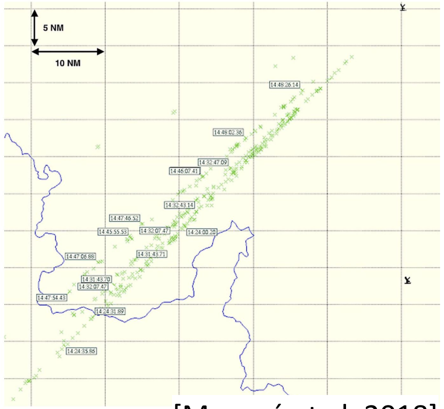


2. Radio blackouts (solar flares)

- in May 1967, a G5 storm associated with a series of X-class flares disrupted the US BMEWS → USAF assumed it was Russians

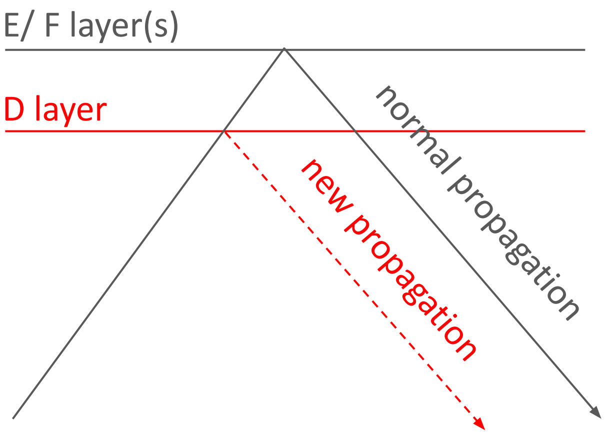
- Nov. 2015, M3.7 a flare caused disruption of secondary air traffic radars (1030 to 1090 MHz), showing "ghost echoes"
  → caused the air traffic to be down for over an hour





[Marqué et al. 2018]

3. Radiation storms (SEP)



- **D layer ionisation** that affects HF comm.
  - signal cannot propagate through D to E or F
  - HF communication cannot be used by A/C for polar routes

- SEPs can cause **surface and internal S/C charging**
  - Halloween 2003 storms, October 29 2003:
    - Goddard's SS Mission Operations Team: 59% of NASA's Earth and space science satellites were affected (data outages, reboots, unwanted thruster firings)
    - USAF operators: over half a satellites lost, up to 3 days to reestablish contact

- pose a **radiation hazard** to space- and high-altitude-based crew

Federated products from the Centre for mathematical Plasma-Astrophysics (KUL)

Virtual Space Weather Modelling Centre | HISTORY | NEW RUN

Welcome to the VSWMC

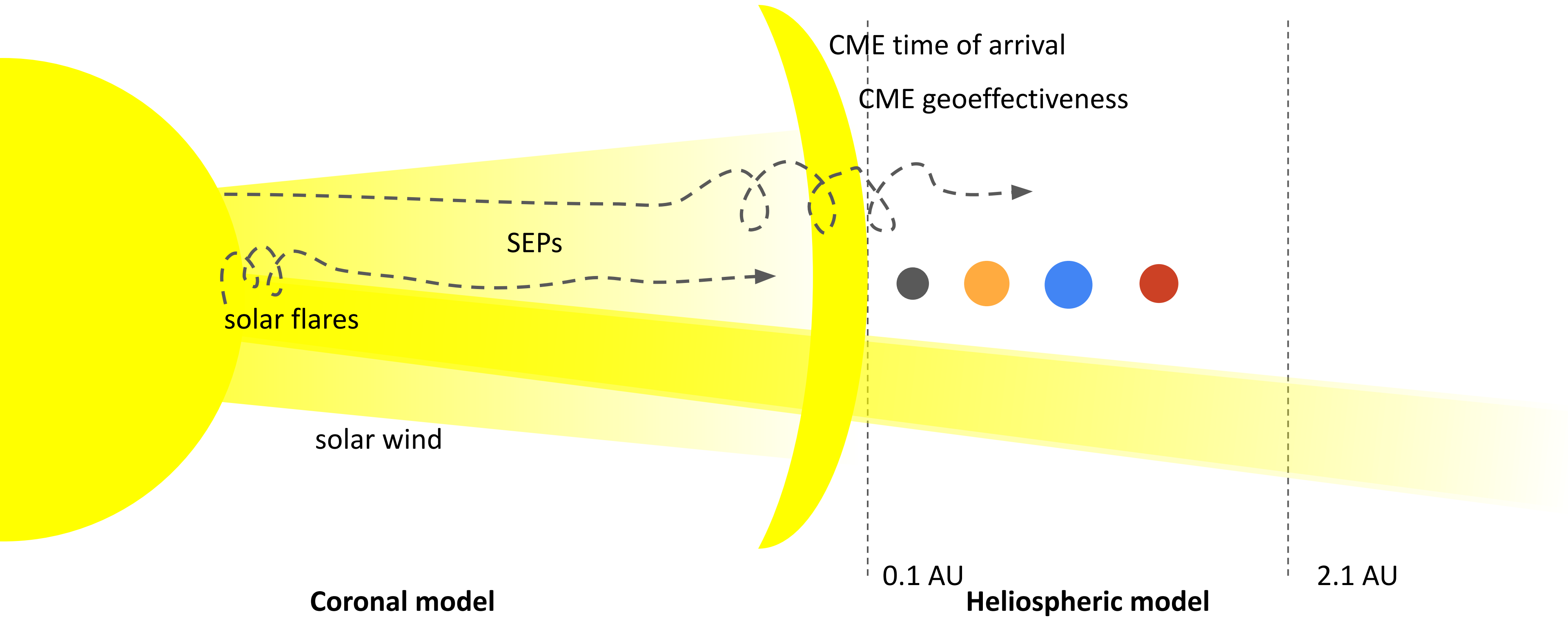
The Virtual Space Weather Modelling Centre (VSWMC) is a full scale, open end-to-end (meaning from the Sun to the Earth) space weather modelling, enabling to combine (*couple*) various space weather models in an integrated tool, with the models located either locally or geographically distributed. Hence, the VSWMC brings together models for different components of the space weather in an integrated environment that enables to run them and to couple them.

About VSWMC | Full-size

Space weather modelling chains

- different SW phenomena have different spatiotemporal scales of relevance → different models to resolve them

[Not to scale]


CME time of arrival
CME geoeffectiveness
SEPs
solar flares
solar wind
0.1 AU
2.1 AU
Coronal model
Heliospheric model

Space weather modelling chains

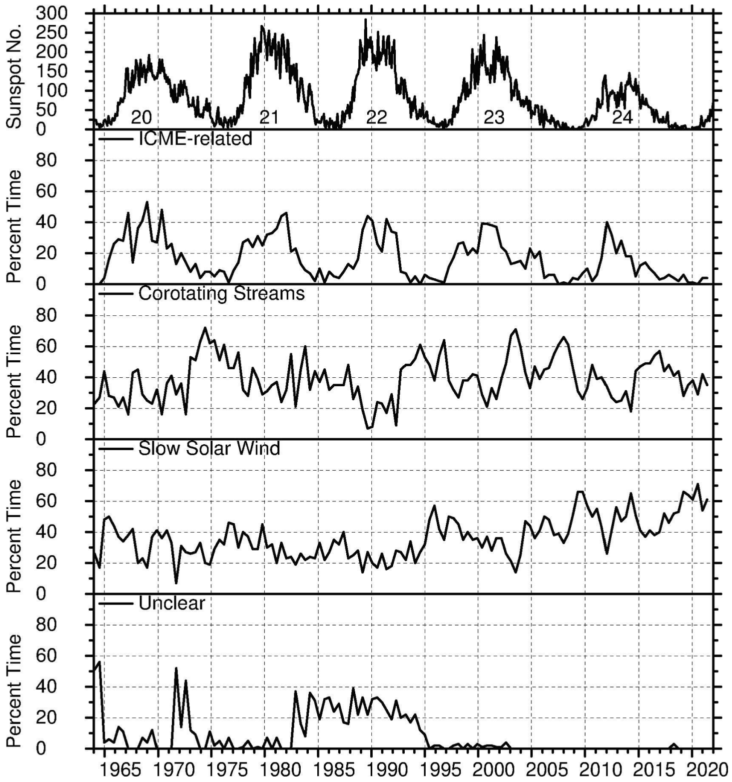
- different SW phenomena have different spatiotemporal scales of relevance → different models to resolve them

- **ESA/VSWMC** (Virtual Space Weather Modelling Centre) [Poedts+ 2020]
- **NASA/CCMC** (Community Coordinates Modelling Center) [Kuznetsova & Center 2022]
- **STORMS** (Solar Terrestrial ObseRvations and Modeling Service) [Rouillard+ 2020]
- **SUSANOO** (Space-weather-forecast-Usable System Anchored by Numerical Operations and Observations) [Shiota+ 2014, Shiota & Kataoka 2016]
- **SWMF** (Space Weather Modeling Framework) [Tóth+ 2005, Gombosi+ 2021]

1. Geomagnetic storms

What drives geomagnetic disturbances?

Temmer+ 2023



- geomagnetic disturbances due to the Bz magnetic field component (→ Dr. Maharana's talk that follows!) → CMEs and CIRs (corotating interaction regions)

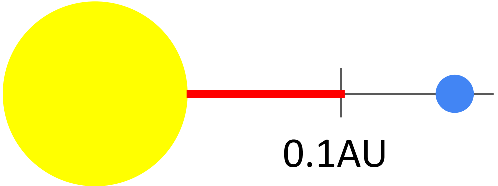
- CMEs are the strongest drivers [Kilpua+ 2017]
  - out of 88 storms during SC 23, **13%** were due to **CIRs** [Zhang+ 2007]
  - for CMEs, **10%** of moderate to large storms are **sheath-induced** [Yermolaev+ 2021]
  - but, t**he recovery phase of CIRs may be longer** than what is typical for CME induced storms [Buresova+ 2014]

Solar wind & CME model types [Temmer+ 2023]

- coronal & heliospheric solar wind:
  - empirical & ML models
  - 1D / reduced order
  - MHD
- CME models:
  - empirical & ML models
  - analytical & drag-based
  - heliospheric reconstruction
  - within coronal/ heliospheric MHD

Model Category/Model name	Input data	Useful references
Empirical Models		
Effective Acceleration Model (EAM)	Coronagraph data	Paouris and Mavromichalaki (2017), Paouris et al. (2021a)
Empirical Shock Arrival model (ESA)	Coronagraph data	Gopalswamy et al. (2001a), Gopalswamy et al. (2005), Manoharan et al. (2004)
Shock ARrival Model (SARM)	Coronagraph and soft X-Rays data	Núñez et al. (2016)
Drag-based Models		
Drag Based Model (DBM)	Coronagraph data	Vršnak et al. (2013), Cargill (2004)
Drag Based Ensemble Model (DBEM)	Coronagraph data	Dumbović et al. (2018), Čalogović et al. (2021)
Drag-based Model Fitting (DBMF)	Coronagraph data	Žic et al. (2015)
ELlipse Evolution model based on Heliospheric Imaging (ELEvoHI)	HI data	Rollett et al. (2016), Amerstorfer et al. (2018)
Reduced-physics Models		
Heliospheric Upwind eXtrapolation with time dependence (HUXt)	Magnetograms and coronagraph data	Owens et al. (2020)
Open Solar Physics Rapid Ensemble Information (OSPREI)	Magnetograms and coronagraph data	Kay et al. (2022)
MHD Models		
ENLIL + Cone	Magnetograms and coronagraph data	Odstrčil and Pizzo (1999b), Odstrcil (2003), Odstrčil et al. (2005)
COROna-HELiosphere (CORHEL)/Magnetohydrodynamic Algorithm outside a Sphere (MAS) + modified Titov-Demoulin (TDm)	Magnetograms and coronagraph data	Riley et al. (2012), Lionello et al. (2013), Török et al. (2018)
Alfvén Wave Solar Model (AWSoM)	Magnetograms and coronagraph data	van der Holst et al. (2014), Jin et al. (2017)
MSFLUKSS + Gibson-Low	Magnetograms and coronagraph data	Singh et al. (2019)
MSFLUKSS + modified spheromak	Magnetograms and coronagraph data	Singh et al. (2020b)
EUropean Heliospheric FORcasting Information Asset (EUHFORIA) + Cone	Magnetograms and coronagraph data	Pomoell and Poedts (2018)
EUHFORIA + Linear Force-Free Spheromak (LFFS)	Magnetograms and coronagraph data	Verbeke et al. (2019b)
ICARUS + Cone	Magnetograms and coronagraph data	Verbeke et al. (2022)
Space-weather-forecast-Usable System Anchored by Numerical Operations and Observations (SUSANOO)-CME	Magnetograms and coronagraph data	Shiota et al. (2014), Shiota and Kataoka (2016)
Heliospheric Reconstruction Approach		
Fixed-Phi Fitting (FPF)	HI data	Rouillard et al. (2008)
Harmonic Mean Fitting (HMF)	HI data	Lugaz et al. (2009b)
Self-Similar Expansion Fitting (SSEF)	HI data	Möstl and Davies (2013)
ELlipse Evolution model based on Heliospheric Imaging (ELEvoHI)	HI data	Rollett et al. (2016), Amerstorfer et al. (2018)
Drag-based Model Fitting (DBMF)	HI data	Žic et al. (2015)
Heliospheric Reconstruction and Propagation Algorithm (HeRPA)	HI data	Paouris and Vourlidas (2022)
ML Models		
CME Arrival Time Prediction Using ML Algorithms (CAT-PUMA)	Coronagraph and solar wind data	Liu et al. (2018)

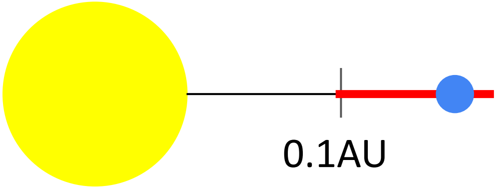
Example global **coronal solar wind** models



- potential-field-extrapolation-based:
  - Potential-Field Source-Surface PFSS [Altschuler & Newkirk 1969]: PF extrapolation
  - Multi-VP [Pinto & Rouillard 2017]: 1D HD + PFSS

- MHD-based:
  - Magnetohydrodynamic Algorithm outside a Sphere MAS [Linker+ 1999]
  - The Alfvén Wave Solar Mode AWSoM [Van der Holst+ 2014]
  - Conservation element and solution element, Harten–Lax–Leer CESE-HLL [Li & Feng 2018]
  - Wind-Predict [Reville+ 2020]
  - COolfluid COronal uNstrUcTured COCONUT [Perri & Leitner+ 2022]

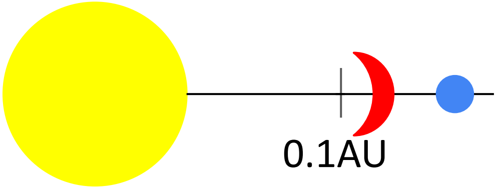
Example global **heliospheric solar wind** models



- 1D & reduced order:
  - Heliospheric upwind extrapolation HUX [Riley & Lionello 2016]: Burger's eq. instead of mom.
  - HUXt [Owens+ 2020]: time-accurate, Burger's eq. instead of mom.
  - Helio1D [Kieokaew+ 2023]: Multi-VP + 1D MHD

- MHD-based:
  - HelioMAS [Linker+ 1999]/ CORHEL-MAS/ CORHEL-WSA [Linker+ 2009]
  - ENLIL [Odstrcil+ 2003]
  - Space weather modelling framework Inner Heliosphere SWMF-IH [Tóth+ 2012]
  - Lyon-Fedder-Mobarry MHD code LFM-helio [Merkin+ 2016]
  - EUropean Heliospheric FORecasting Information Asset EUHFORIA [Pomoell & Poedts 2018]
  - ICARUS [Verbeke+ 2022]: EUHFORIA-based with adaptive mesh refinement

Example global **heliospheric CME** models



- empirical:
  - Empirical shock arrival model ESA [Gopalswamy+ 2001]
  - Effective acceleration model EAM [Paouris & Mavromichalaki 2017]
  - Shock arrival model SARM [Núñez+ 2016]
  - CME Arrival Time Prediction Using Machine learning Algorithm CAT-PUMA [Liu+ 2018]

- drag-based:
  - Drag based model DBM [Vršnak+ 2012]
  - Drag based model fitting DBMF [Žic+ 2015]
  - ELEvoHI [Hinterreiter+ 2021]: ellipse evolution with a deformable front

- plus implementations directly into coronal & heliospheric MHD

Where are we? CMEs: time of arrival, geo-effectiveness

- Riley+ 2018 with CME Scoreboard:
  - CME ToA accurate to within about 10 h
  - the best models had a **MAE (mean absolute error) of 13 h, SD (standard deviation) of 15 h**

- Kay+ 2024 updating Riley+ 2018:
  - a **MAE of 13.2 hr, SD of 17.4 hr**
  - not much change compared to 2018

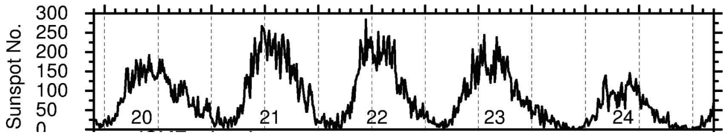
- Vourlidas+ 2019: currently, **not possible to predict B_z reliably beyond 40 – 60 min** (from L1)

- Riley & Ben-Nun 2021:
  - uncertainty in initial CME parameters → 2.5 and 7.5 h of the total ToA uncertainty
  - the ambient solar wind structure was the largest source of uncertainty

CMEs & solar wind: Where are we still lacking?

- understanding:
  - what causes **coronal heating** and **fast & slow solar wind**?
  - what is the **internal structure of CMEs** & what “launching” parameters to use?
- observations:
  - what is the B on the **far side**? (Jeong+ 2020: AI to get far-side B from EUV, but not always available)
  - what do the **poles** of the Sun look like? (here, SolO will help) 
  - what is the **coronal magnetic field** (can we use more advanced local codes like Bifrost/ MURaM)?
- modelling complexity:
  - resolution of **time-accurate details** (e.g., temporal evolution of CHs, solar wind)
  - inclusion and effects of **small scale structures**
  - inclusion of **cycle-to-cycle** phenomena

Temmer+ 2023



2. Solar flares

What drives solar flares? [Georgoulis+ 2024]

- non-potential, complex AR, if enough “free magnetic energy” is available
  - in short, to flare, an AR region but be **“big, bad and angry”**
- important for CME & SEPs ⟶ a CME from an AR will usually be associated with a flare

- almost entirely relies on statistical correlations between the solar magnetic field and flare characteristics (e.g., the McIntosh groups); some more advanced use PFEs

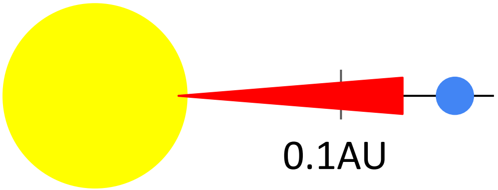
- forecasting windows are typically around a day:
  - the flare “starts” at unobservable spatial scales ⟶ stochasticity [e.g. Lu & Hamilton 1991, Vlahos & Georgoulis 2004] at very short time-scales that we cannot predict
  - at longer time-scales, the magnetic flux evolution in ARs may start to vary too much

Flare model types [Georgoulis+ 2024]

- physics based
  - Sandpile/ avalanche models
  - MHD
- statistical & AI/ML based
  - based on correlations between flaring and photospheric information
- ensemble
  - those that involve a combination of different predictors together (Guerra+ 2020: linearly combining ASAP, ASSA, MAG4, MOSWOC, NOAA, and MCSTAT)

Solar flares		
Prediction Method	Input Data	References (suggested)
Physics-based		
Sandpile/Avalanche models	Assimilation & synthetic data; GOES X-ray time series	Bélanger et al. (2007), Strugarek and Charbonneau (2014), Morales and Santos (2020), Thibeault et al. (2022)
Statistical		
Fractal/ Multifractal	LOS magnetograms;	McAteer et al. (2005), McAteer et al. (2010), Conlon et al. (2010)
Bayesian	Poisson probabilities; LOS magnetograms	Wheatland (2004), Wheatland (2005), Georgoulis and Rust (2007), Georgoulis (2012), Kontogiannis et al. (2017)
Discriminant Analysis	LOS magnetograms; SHARP metadata & HARP data & NOAA/SWPC metadata & GONG Dopplergrams	Leka and Barnes (2003b); Barnes et al. (2007); Leka et al. (2018); Komm et al. (2011); Welsch et al. (2009); Barnes and Leka (2006)
Superposed Epoch Analysis	LOS magnetograms	Mason and Hoeksema (2010), Reinard et al. (2010)
Best fit	Sunspot properties, HARP magnetograms, assimilation & synthetic data from avalanche/ sandpile models	Bélanger et al. (2007), Strugarek and Charbonneau (2014), Korsós et al. (2015), Korsós et al. (2020), Morales and Santos (2020), Thibeault et al. (2022)
Decision boundary	LOS magnetograms & NOAA/SWPC metadata	Huang and Wang (2013)
Poisson	Sunspot properties; NOAA/SWPC data; Forecaster in the loop	Gallagher et al. (2002), Wheatland (2004), Wheatland (2005), Berghmans et al. (2005), Bloomfield et al. (2012), Crown (2012), Lee et al. (2012), Devos et al. (2014), Murray et al. (2017), Kubo et al. (2017), McCloskey et al. (2018), Falco et al. (2019)
Timeseries/ Evolution	HMI magnetograms; SHARP metadata & HARP data & NOAA/SWPC metadata, NOAA/SWPC metadata; SHARP metadata & timeseries forest	Muranushi et al. (2015), McCloskey et al. (2018), Leka et al. (2018), Cinto et al. (2020), Ji et al. (2020) (All Clear)
Artificial Intelligence		
Machine Learning		
Supervised	LOS magnetograms; LOS magnetograms & continuum; LOS magnetograms & sunspot properties; Solar Monitor metadata; SHARP metadata; NOAA/ SWPC metadata; HARP magnetograms; HARP magnetograms & AIA images; SHARP metadata & polar HMI magnetograms; IRIS data; LOS magnetograms & AIA images; SHARP metadata, HARP magnetograms & computational topology; LOS magnetograms & sunspot properties	Qahwaji and Colak (2007), Colak and Qahwaji (2009), Li et al. (2007), Song et al. (2009), Yu et al. (2009), Yuan et al. (2010), Steward et al. (2011), Steward et al. (2017), Ahmed et al. (2013), Lee et al. (2013), Bobra and Couvidat (2015), Boucheron et al. (2015), Al-Ghraibah et al. (2015), Raboonik et al. (2016), Nishizuka et al. (2017), Liu et al. (2017), Barnes et al. (2017), Florios et al. (2018), Campi et al. (2019), Domijan et al. (2019), Alipour et al. (2019), Cinto et al. (2020), Deshmukh et al. (2020), Abduallah et al. (2021), Korsós et al. (2021), Aktukmak et al. (2022), Huwyler and Melchior (2022), Sinha et al. (2022)
Hybrid (Supervised & Unsupervised)	NOAA/SWPC metadata; SHARP metadata; HARP magnetograms	Li et al. (2011), Benvenuto et al. (2018), Campi et al. (2019), Deshmukh et al. (2022)
Deep Learning		
Video Classification	HARP magnetograms	Guastavino et al. (2022)
Deep Neural Networks	LOS magnetograms; Solar Monitor metadata; HARP magnetograms & AIA images; Full-disk HMI images; HARP magnetograms & Intensity; SHARP metadata timeseries; SWPC GOES timeseries	Huang et al. (2018), Nishizuka et al. (2018), Zheng et al. (2019), Domijan et al. (2019), Yi et al. (2020), Nishizuka et al. (2020), Nishizuka et al. (2021), Abed et al. (2021), Pandey et al. (2021), Pandey et al. (2022), Chen et al. (2022), Abduallah et al. (2023)
Knowledge-informed	Magnetogram Images	Li et al. (2022)
DL model fusion	HARP magnetograms & SHARP metadata; SHARP & SMARP metadata; HMI and MDI images	Tang et al. (2021), Sun et al. (2022), Liu et al. (2022)
Long short-term memory network	SHARP metadata with or without flare history	Liu et al. (2019), Jiao et al. (2020), Wang et al. (2020)
Ensemble		
Predictor teams	LOS magnetograms	Huang et al. (2010)
Combination of probabilistic predictions from different methods	AR or full-disk probabilities & SWPC flare data;	Guerra et al. (2015), Guerra et al. (2020)

Example flare models



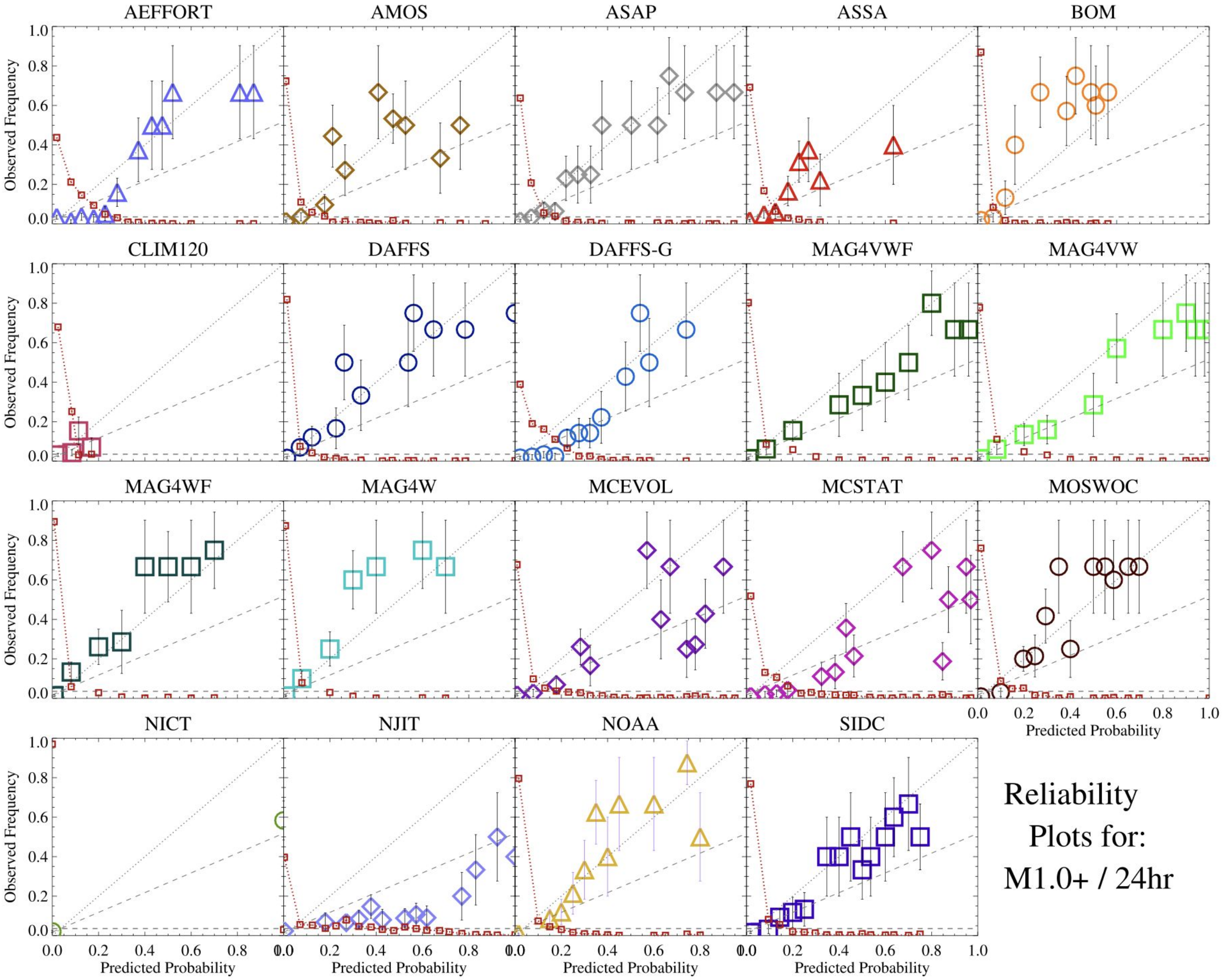
- McIntosh classification based:
  - Automatic McIntosh-based Occurrence probability of Solar activity AMOS [Lee+ 2012]
  - Automatic Solar Synoptic Analyzer ASSA [Bloomfield+ 2012]
  - Automated Solar Activity Prediction ASAP, with CNN [Abed+ 2021]

- Other magnetic parameter based:
  - Athens Effective Solar Flare Forecasting A-EFFort: computes the effective connected magnetic field strength → flaring probability [Georgoulis & Rust 2007]
  - MAG4/ MagPy: estimates magnetic free energy from the gradient of B across the neutral line, the magnetic shear angle across the neutral line and similar [Falconer+ 2014]

- Physics-based
  - PLUTO adaptation [González-Servín & González-Avilés, 2024]

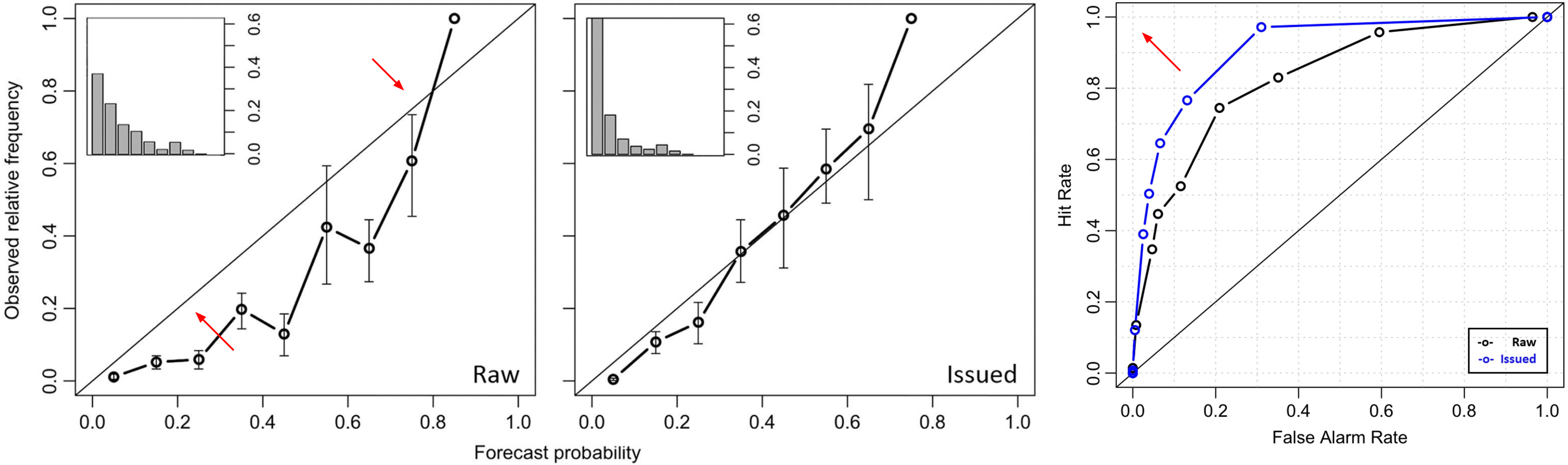
Luka+ 2019

- here for M-class flares
- dotted line: perfect score
- dashed-sloped line: the no-skill limit
- red squares line: fraction of total sample where a forecast exists for each bin



Where are we with flare modelling? [Murray+ 2017]

- calculated based on historical flare rates for each McIntosh class
- still far better if helped by an operator



Solar flares: where are we still lacking?

- statistics/ sample-related issues
  - cycle to cycle variations
  - class imbalance
    - ratio between the flaring & non-flaring AR samples in Angryk+ 2020 is ∽ 60:1
  - usable data limited to 40 (LOS) - 70 (vector) degrees EW from the central meridian due to magnetogram curvature effects

  - AI/ ML-based: *'"supervised deep learning algorithm will generally achieve acceptable performance* ***with around 5,000 labeled examples per category*** *and will match or exceed human performance when trained with a dataset containing* ***at least 10 million labeled examples****": we have been observing flares, CMEs and SEPs events for a few decades and each typical 11-year solar cycle includes a few tens of thousands of CMEs, several hundred flares of GOES class M and above, and a couple of hundred SEP events, at best'* [Georgoulis+ 2024]

3. Solar energetic particles

What drives SEP events? [Whitman+ 2023]

- associated with both flares in the corona and with diffusive shock acceleration (DSA) at CMEs
    - intensity correlated with flare parameters and CME speed
      → SEP predictions are only as good as CME/ flare predictions

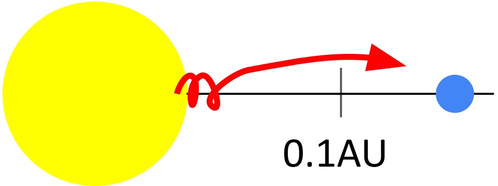
- can be diagnosed through radio bursts; by stream of electrons causing radio emission, accelerated also when high-energy ions are
    - type II: source close to the sun → associated with solar flares
    - type III: source moves at a ~1 000 km/s → associated with CME

SEP model types [Whitman+ 2023]

- types of models:
  - empirical models
    - with or without machine learning
    - either binary (yes/ no for a given threshold) or deterministic (time/ of arrival/ peak etc.)
  - physics based models
    - transport equations with diffusion, convection, cooling…
    - numerically intensive
    - generally not for forecasting, qualitative

Model	Type	Magnetograms	Optical Imaging	EUV Imaging	Soft X-ray Intensity	Ground-based Radio	Space-based Radio	Coronagraph	Solar Wind (n,T,p,v)	Suprathermal Particles	Energetic Protons	Energetic Electrons	Neutron Monitors
ADEPT	Empirical										x		
AFRL PPS	Empirical		x		x	x							
Aminalragia-Giamini model	ML			x	x								
AMPS	Physics-based	x		x				x					
Boubrahimi model	ML				x						x		
COMESEP SEPForecast	Emp. & Physics			x	x			x					x
EPREM	Physics-based	x		x				x		x			
ESPERTA	Emp. & ML			x	x		x				x		
FORSPEF	Empirical	x	x		x		x	x					
GSU	ML	x											
iPATH	Physics-based	x		x				x	x	x			
Lavasa Model	ML		x		x			x					
MAG4	Empirical	x	x		x								
MagPy	Empirical	x	x		x								
MEMPSEP	ML	x		x	x		x	x	x	x	x	x	
M-FLAMPA	Physics-based	x		x				x					
PARADISE	Physics-based	x		x				x					
PCA model	Empirical				x			x					
PHSVM	ML				x						x		
PROTONS	Empirical				x	x							
REleASE	Empirical											x	
Sadykov's Model	ML	x			x	x					x		
SAWS-ASPECS	Empirical	x	x		x			x			x	x	x
SEPCaster	Physics-based	x		x				x	x				
SEPMOD	Physics-based	x		x				x					
SEPSTER	Empirical			x				x	x				
SEPSTER2D	Empirical			x				x	x				
SMARP Model	ML	x											
SOLPENCO	Physics-based			x				x					
SOLPENCO(2)	Physics-based			x				x	x		x		
South African model	Physics-based			x	x			x					
SPARX	Physics-based			x	x								
SPREAdFAST	Physics-based	x		x				x		x	x		
SPRINTS	ML	x		x	x						x		
STAT	Physics-based	x		x				x		x			
UMASEP	Empirical				x	x					x		
Zhang model	Physics-based	x		x				x	x				
Total		19	6	21	19	4	3	21	7	5	11	3	2

Example SEP models



- physics-based:
  - iPATH 2D model for diffusive shock acceleration at CME shocks [Hu+ 2017]
  - SPE Threat Assessment Tool STAT(CORHEL + EMMREM) [Linker+ 2019]
  - Particle Radiation Asset Directed at Interplanetary Space Exploration PARADISE [Wijsen+ 2020]: coupled with EUHFORIA/ ICARUS (+ COCONUT)
  - SEP model SEPMOD [Luhmann+ 2017]: (WSA + Enlil)
- empirical:
  - Solar Particle Radiation Advanced Warning System SAWS-ASPECS [Anastasiadis+ 2017]
  - Space Radiation Intelligence System SPRINTS [Engell+ 2017]
  - SEP prediction inspired by STEREO observations SEPSTER [Richardson+ 2014]
  - High Energy Solar Particle Events forecasting and Analysis HESPERIA: proton flux determined from measured (near-)relativistic electron flux [Malandraki & Crosby 2018]

Where are we with SEP modelling?

- Air Force Research Laboratory Proton Prediction System AFRL PPS [Smart+ 1979]
  - **POD: 0.4 - 0.66, FAR: 0.49 - 0.83** (depends on the freq. range of radio burst)
- FOrecasting Solar Particle Events and Flares FORSPEF [Anastasiadis+ 2017]
  - **POD: 0.4 - 0.71, FAR: 0.41 - 0.57** (depends on if based on flare data/ CME data or SXR & radio fluence)
- MAG4 [Falconer+ 2011]
  - **POD: 0.31 - 0.38, FAR: 0.48 - 0.5** (depends on if there is flaring)
- Solar Particle Radiation SWx SPARX [Marsh+ 2015]
  - **POD: 0.5 - 0.77, FAR: 0.44 - 0.57** (depends on the channel, 1 or 10 pfu)
- The University of Malaga Solar Energetic Particles UMASEP [Núñez 2011]
  - **POD: 0.54 - 0.82, FAR: 0.22 - 0.3** (depends on SEP energy channel)

SEPs: Where are we still lacking? [Whitman+ 2023]

- for physics-based modelling:
  - many **poorly constrained parameters** that affect the results greatly, e.g. diffusion coefficients, or the seed population spectral shape
  - placement of the **inner boundary** → particle acceleration at the beginning of an SEP event might happen below $2R_S$ [Mäkelä+ 2015]
  - very **computationally expensive** (not used for forecasting)
  - usually only **one-way coupling** with the background solar wind

- for empirical, especially ML/AI based:
  - challenges to prepare **uniform & reliable observational databases**
  - challenges with **statistics**; e.g. in SC 24, only 101 days of >10 pfu 10 MeV proton flux, vs 3400 days

The verdict?

Which models are the “best”?

- there are many models, and new ones are added every year

- which ones are “better” than others depends on the use case
    - operational space weather forecasting vs fundamental studies of solar physics

- to determine which ones are “better” than others, we need more **robust validation and comparisons**
    - continuous daily/ weekly runs without parameter adjustments
    - test the output parameters that matter for the users

→ e.g. CCMC scoreboards: CMEs, flare, SEP probability, SEP intensity, SEP all clear

Example CCMC CME scoreboard

CME: 2024-09-08T01:36:00-CME-001

CME Note: This CME is visible to the NW in SOHO LASCO C2, C3, and as a partial halo in STEREO A COR2 imagery. The source is a filament eruption centered near N14W20 which deflects NW as it erupts based on SDO/AIA 304 imagery. The eruption begins around 2024-09-08T00:00Z. A faint EUV wave is visible traveling N/NE of the source location despite the filament material deflecting NW as seen in SDO/AIA 193 and GOES SUVI 284. This eruption is also visible in STEREO A EUVI 304.

Predicted Shock Arrival Time	Difference (hrs)	Confidence (%)	Submitted On	Lead Time (hrs)	Predicted Geomagnetic Storm Parameter(s)	Method	Submitted By	
2024-09-10T19:51Z	----	----	2024-09-09T08:02Z	35.82	Max Kp Range: 3.0 - 5.0	SARM	Marlon Nunez (UMA)	Detail
2024-09-10T20:17Z (-4.97h, +8.01h)	----	50.0	2024-09-08T17:42Z	50.58	----	CMEFM v.0.1	Garrett Imhoff (Other)	Detail
2024-09-10T22:00Z	----	30.0	2024-09-08T19:00Z	51.00	Max Kp Range: 4.0 - 6.0	WSA-ENLIL + Cone (Met Office)	Met Office (Met Office)	Detail
2024-09-10T23:45Z (-7.0h, +7.0h)	----	----	2024-09-09T07:26Z	40.32	----	EAM (Effective Acceleration Model)	Evangelos Paouris (UoA)	Detail
2024-09-10T23:51Z (-7.0h, +7.0h)	----	----	2024-09-08T17:30Z	54.35	Max Kp Range: 4.0 - 6.0	WSA-ENLIL + Cone (NASA M2M)	Carina Alden (M2M Office)	Detail
2024-09-11T00:00Z (-7.0h, +7.0h)	----	----	2024-09-09T07:24Z	40.60	----	EAM (Effective Acceleration Model)	Evangelos Paouris (UoA)	Detail
2024-09-11T01:56Z	----	43.3333	---	---	Max Kp Range: 3.66667 - 5.66667	Average of all Methods	Auto Generated (CCMC)	Detail
2024-09-11T23:52Z (-6.93h, +10.03h)	----	50.0	2024-09-08T17:43Z	78.15	----	CMEFM v.0.1	Garrett Imhoff (Other)	Detail

What next?

```
# Fluids Properties
Simulator.SubSystem.MultiFluidMHD2D.ConvTerm.molecularMass1 = 1.67262177774e-25
Simulator.SubSystem.MultiFluidMHD2D.ConvTerm.molecularMass2 = 1.67262177774e-24
Simulator.SubSystem.MultiFluidMHD2D.ConvTerm.lightSpeedMax = 10000. #299792458
Simulator.SubSystem.MultiFluidMHD2D.ConvTerm.lightSpeedMF = 10000. #299792458
```

electron mass
ion mass

- Asvestari+ 2019, Caplan+ 2021: coronal model–model and model–observation comparison: results strongly depend on which model combination was used and how the transition between the models was performed

- Temmer+ 2023: *"An objective evaluation of the performance of different models … requires* ***model developers to be transparent about their (often hidden) model parameters*** *and how they are tuned"*
  → honest and thorough documentation is key
    - good documentation & open source availability would also allow modellers to build up on existing codes instead of just always creating new ones

"I just want a model that works." -- a user

"Here are 30 that perhaps do sometimes." -- the scientist

TRL	Definition
1	Basic principles observed and reported.
2	Technology concept and/or application formulated.
3	Analytical and experimental critical function and/or characteristic proof of concept.
4	Component and/or breadboard validation in laboratory environment.
5	Component and/or breadboard validation in relevant environment.
6	System/sub-system model or prototype demonstration in an operational environment.
7	System prototype demonstration in an operational environment.
8	Actual system completed and "flight qualified" through test and demonstration.
9	Actual system flight proven through successful mission operations.

1 - 3 new/ year | ??? | probably still something from the 80's

TRL 1 - 4 | TRL 5 - 7 | TRL 8 - 9

scientists → users

"... this development will contribute towards more accurate space weather forecasting…"

- …will it? Not really if the development stops at TRL 4.

“I just want a model that works.” -- a user

“Here are 30 that perhaps do sometimes.” -- the scientist

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1 - 3 new/ year — TRL 1 - 4

??? — TRL 5 - 7

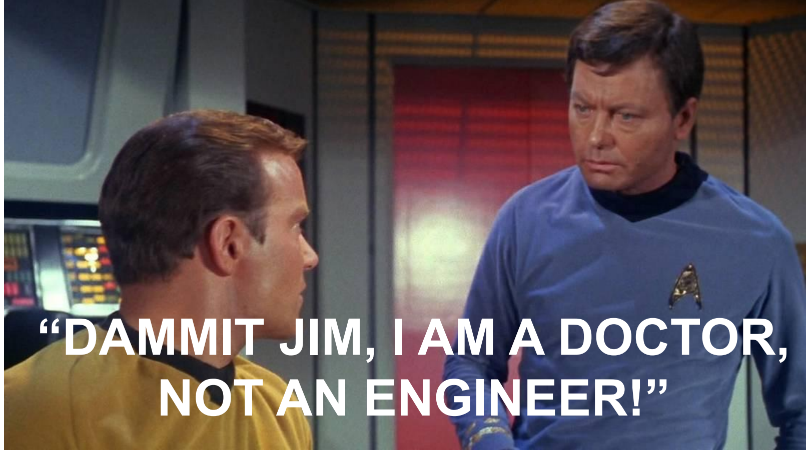
probably still something from the 80’s — TRL 8 - 9

scientists → users

→ **<u>need to improve the R2O2R link</u>** (research to ops to research):

- making our models more operation-focused
- getting feedback from the users to improve the models

How so many models, when so few are actually used? My thoughts



- raising TRL from 4 - 5+ might be:
  - less intellectually & scientifically interesting
  - more work & more difficult to publish
  - “not our work” (whose is it then?)
  - often requires **communication with the users**

- but communication with the potential users remains problematic:
  - they largely do not even read papers
  - the communication should happen in the language of the user
  - few benefits for the researcher putting the work in
  - currently few places to meet

Conclusions

- space weather can have pronounced effects on our society, **even cause lives**
- many new models are being developed, of different complexities, using different inputs and producing different outputs
- still, our forecasts are not making use of all this effort as most of these models are at low technology readiness
- improving the actual SW capability, next to developing new and "better" models, also requires doing (and **rewarding**):
  - honest and thorough **documentation** (that might also lead to more collaboration)
  - robust model **validation** and **comparisons**, and
  - good and frequent **communication with the actual users**

Thank you for your attention!

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