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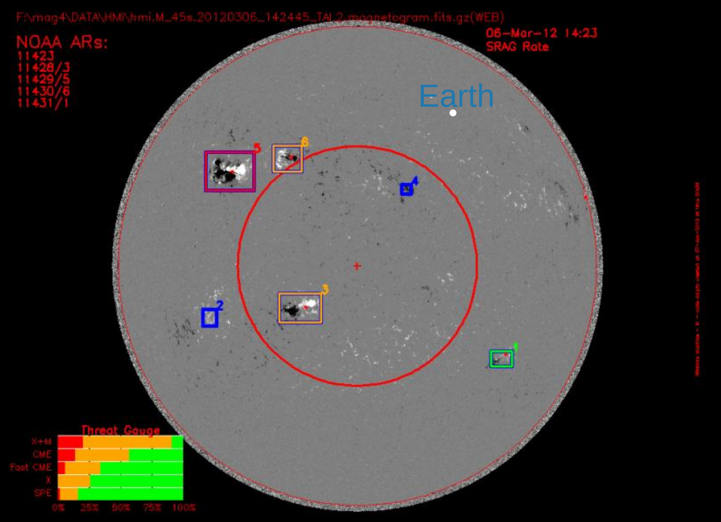
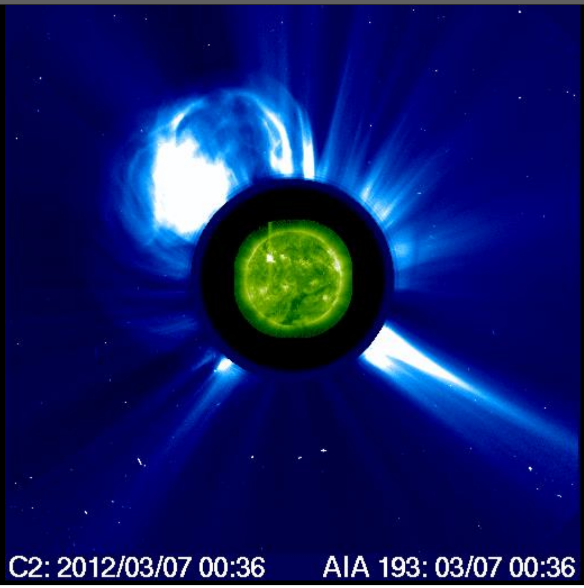


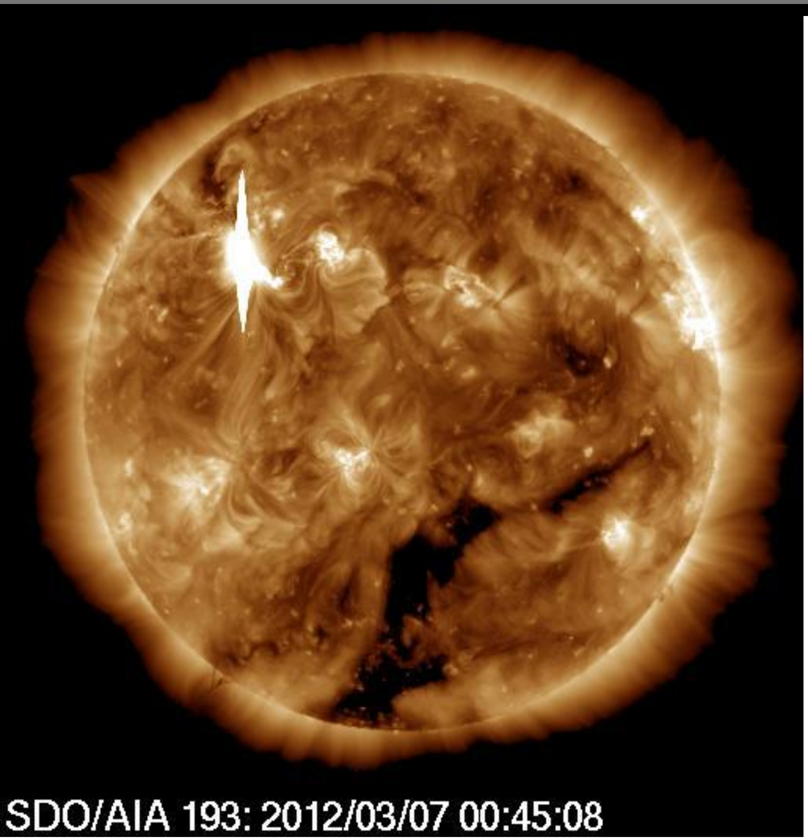


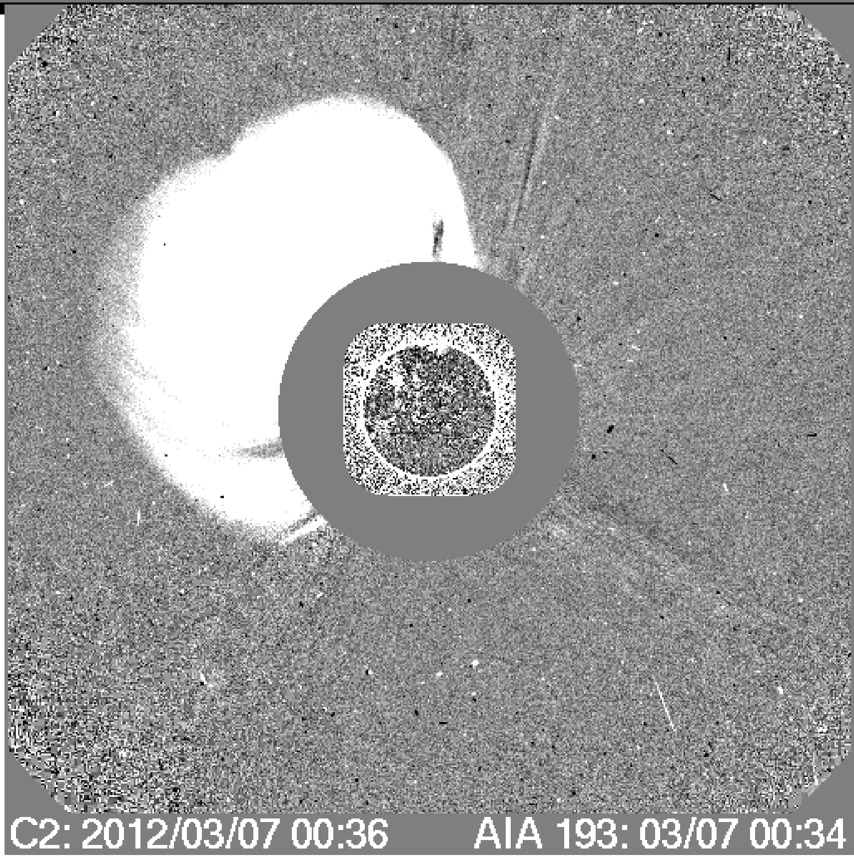
MAG4: An All-Clear Space-Weather Forecasting System

David Falconer (ZP13/UAH-CSPAR) & Nasser Barghouty (ZP12)

MSFC Innovation Day - November 1, 2016

The Solar Particle Event (SPE) Threat





- A major eruptive flare
  - the most powerful explosions in the solar system
  - dangerous to unshielded astronauts

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MAG4 and Human Spaceflight

- Space radiation mitigation was rated the highest priority technology for human spaceflight in NRC's 2012 report on NASA's technology roadmaps

- NASA lists space radiation mitigation as one of eight core technology investments in its *Space Strategic Technology Plan* (2013)

- NASA lists the following five specialty areas as priority areas for its space radiation mitigation core area:

  monitoring
  detection
  forecasting
  risk assessment
  mitigation

MAG4 and Human Spaceflight

The ability to accurately forecast space-weather conditions and space-radiation levels is one of the highest (**level 3**) priorities on the agency's roadmap for ***Human Health, Life Support, and Habitation Systems*** (**"TA 6.5.4"**)

↓

"Technology Area 6.5.4 Space Weather Prediction: The focus of this area is to advance improvements in solar particle event (SPE) forecasting and alert systems to minimize operational constraints for missions outside the protection of the Earth's geo-magnetic field**."** **http://www.nasa.gov/offices/oct/home/roadmaps/index.html**

↓

SPE is one of two major sources of highly-ionizing radiation levels facing human spaceflight in particular as well as space exploration in general

↓

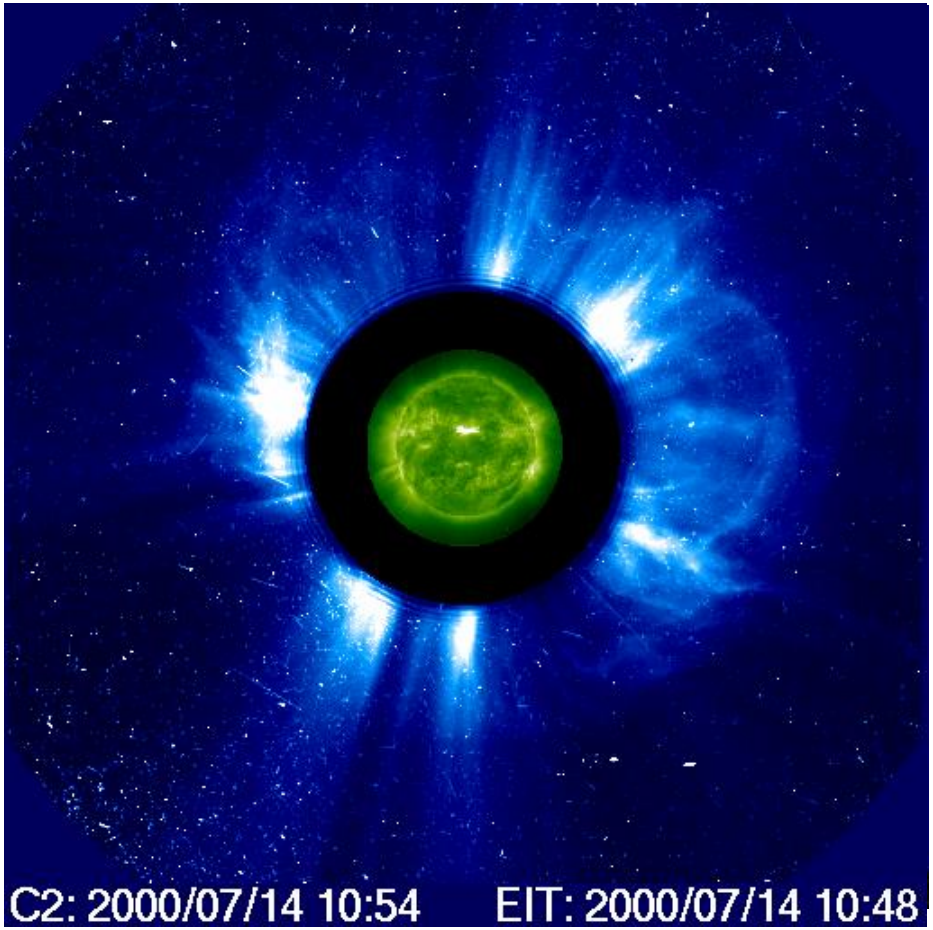
The technical challenges we face in understanding (and mitigating) these two sources are quite varied and complex…

↓

…and this is where MAG4 makes the difference!

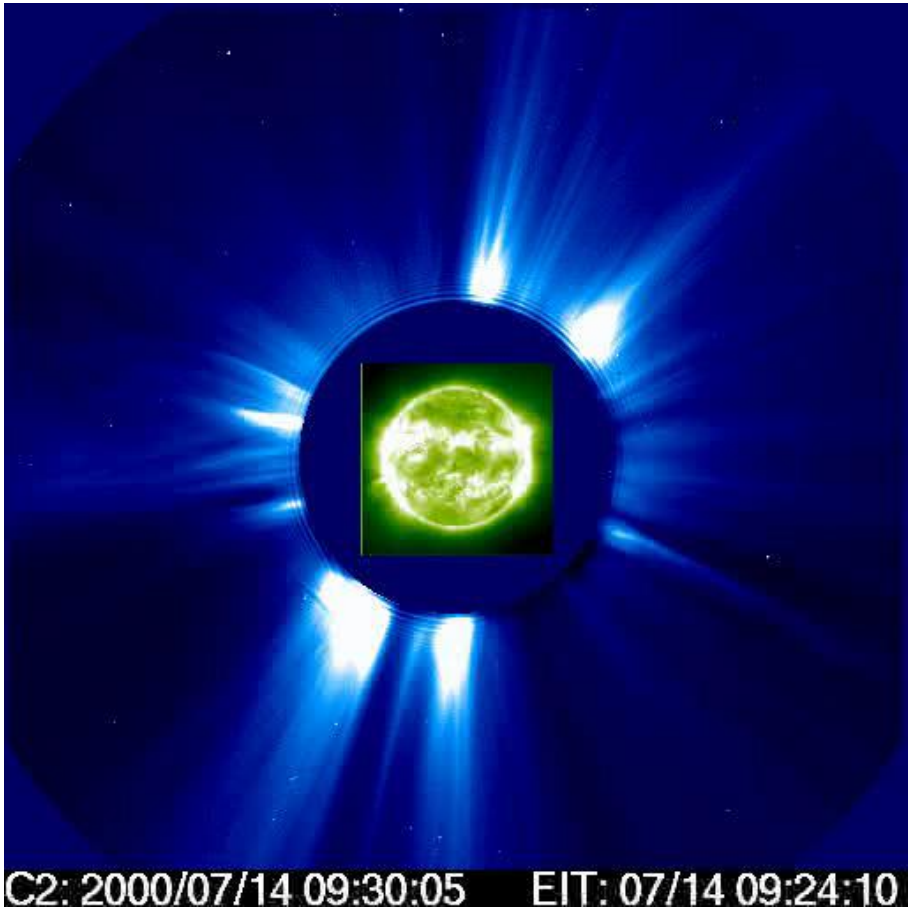
The Threat

- Eruptive flares can produce an SPE
- SPEs arrive 10 minutes to a day after the light of the flare
- For unshielded astronauts, SPEs can cause radiation damage and possibly lethal radiation doses

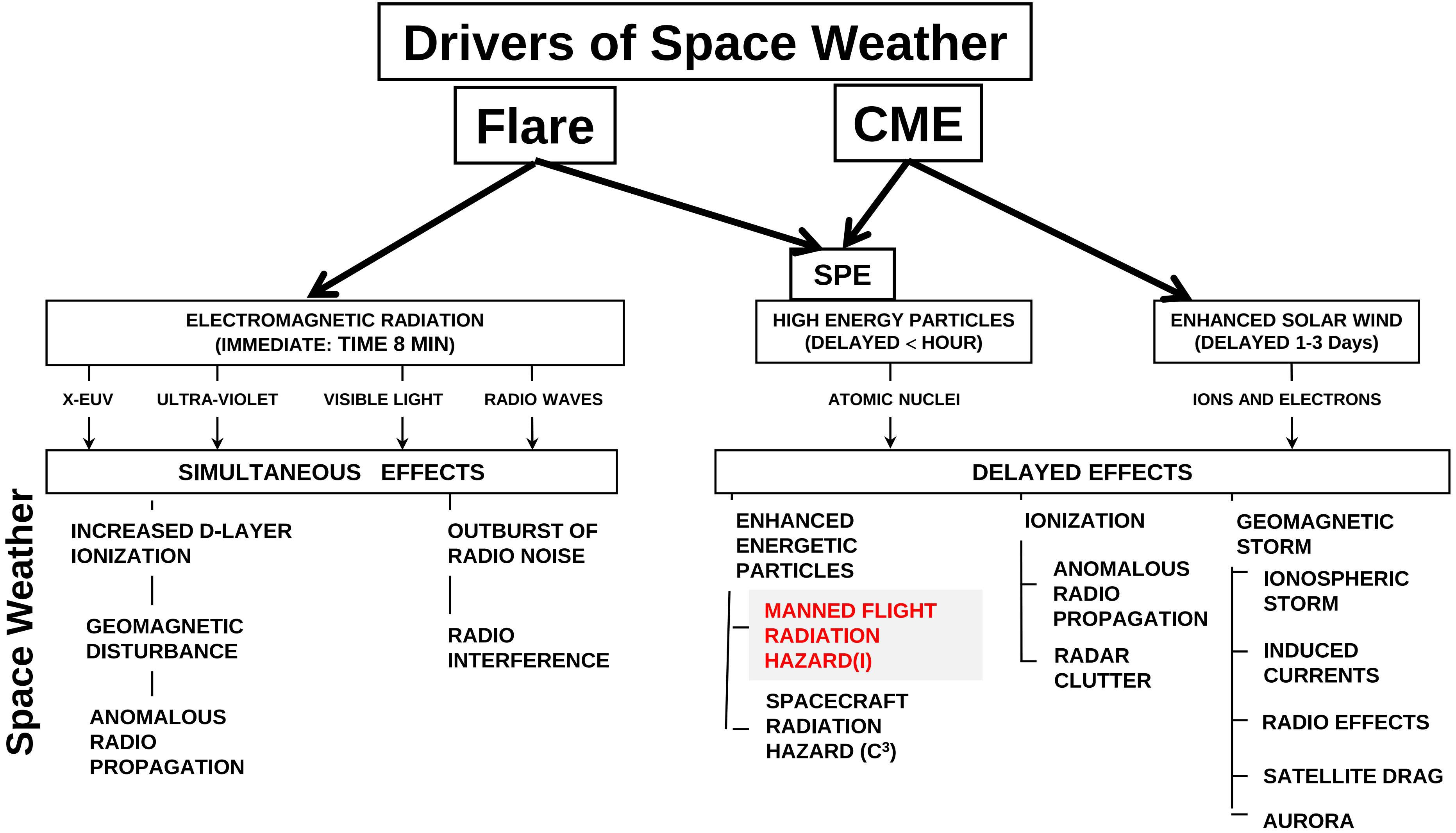


SPE Overview

- Forecasting flares and CMEs is the first step to forecasting dangerous space weather
- SPEs are especially dangerous to astronauts especially during EVAs or away from LEO
- **One of the best forecasts is All Clear Forecasts**

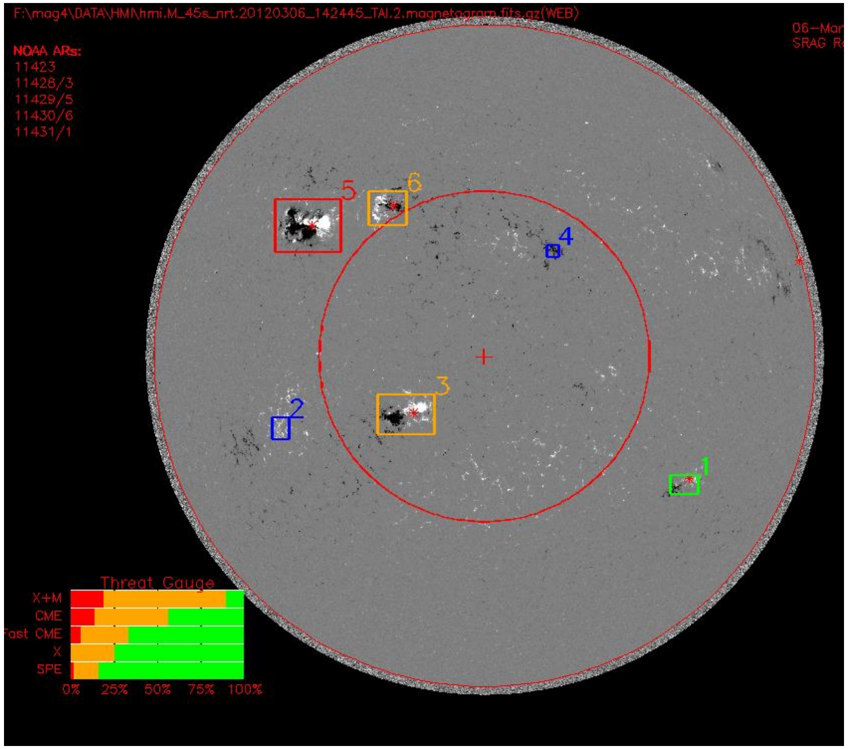


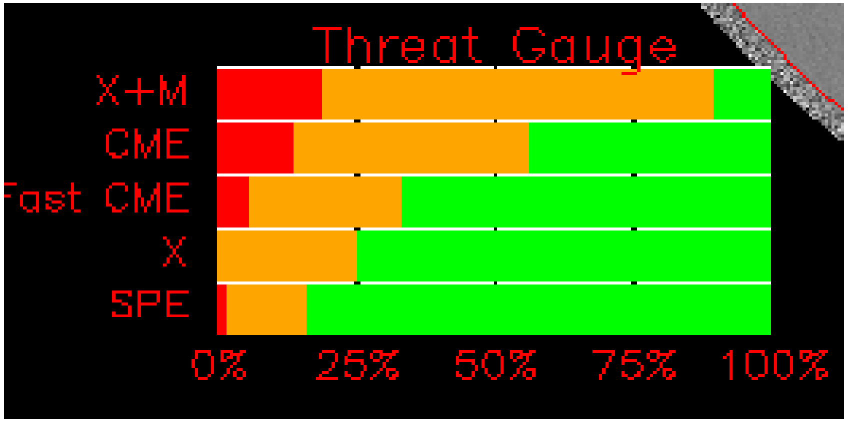
Space Weather Overview



MAG4 Solution

- Flares like earthquakes are very difficult to predict
- Historical records can provide empirical base forecasts
- MAG4 (Magnetogram Forecast) uses empirical data to predict the event rate of dangerous solar activity
- It does this automatically 24/7, making new forecasts every 96 minutes
- It forecasts **major flares**, coronal mass ejections (**CME**s), and **SPE**s

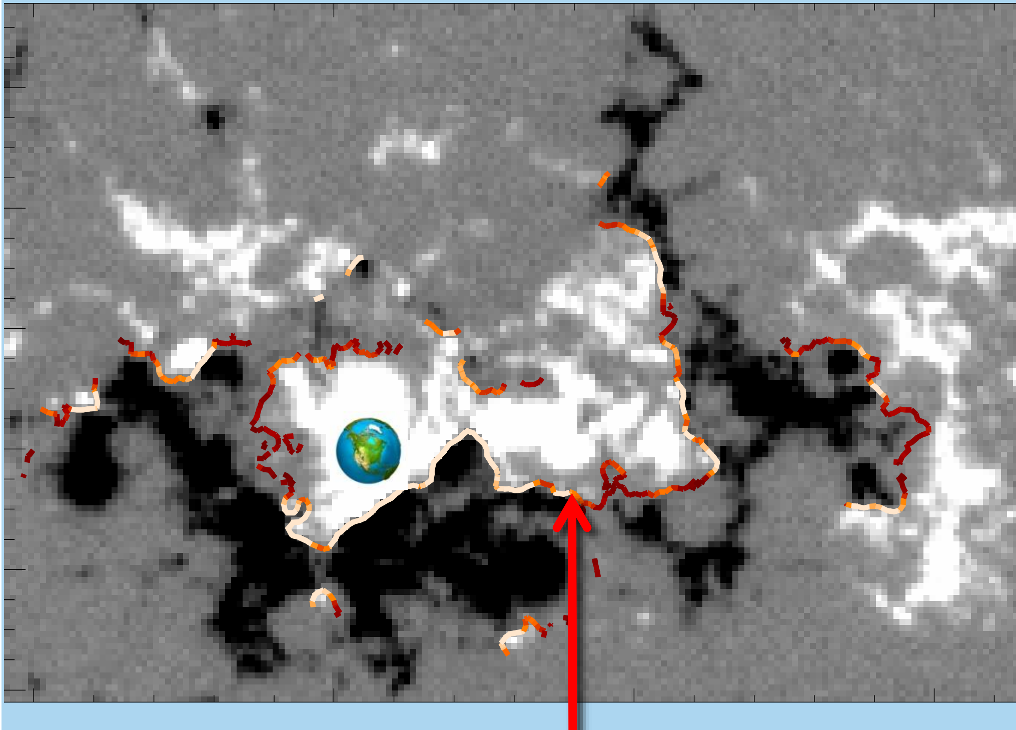




MAG4 Science

- Flares and CMEs are powered by magnetic energy stored in the corona
- Direct measurements of coronal magnetic energy are inaccurate
- When the magnetic field is stressed, energy is stored and available for “explosive release”; more energy is stored, greater the chance of a major flare
- MAG4 uses a proxy to quantify the free energy stored in an active region
- Event rates are correlated with the magnitude of the free-magnetic-energy proxies

- **Data driven forecasts**



Neutral Line, color coded for gradient

500 G

-500 G

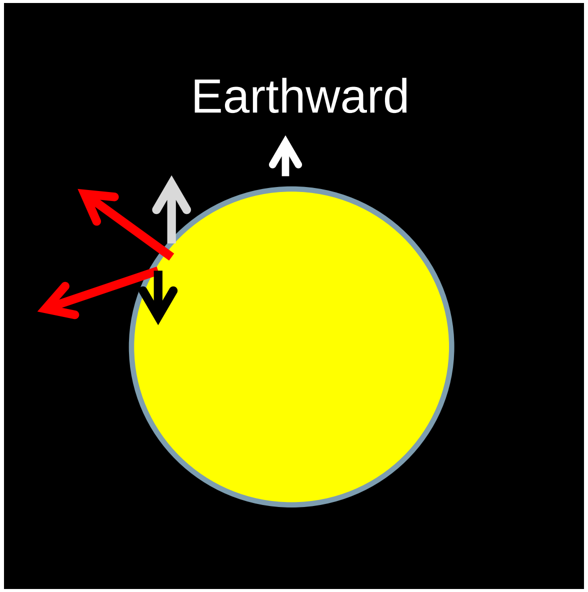
0.1G/km

0 G/km

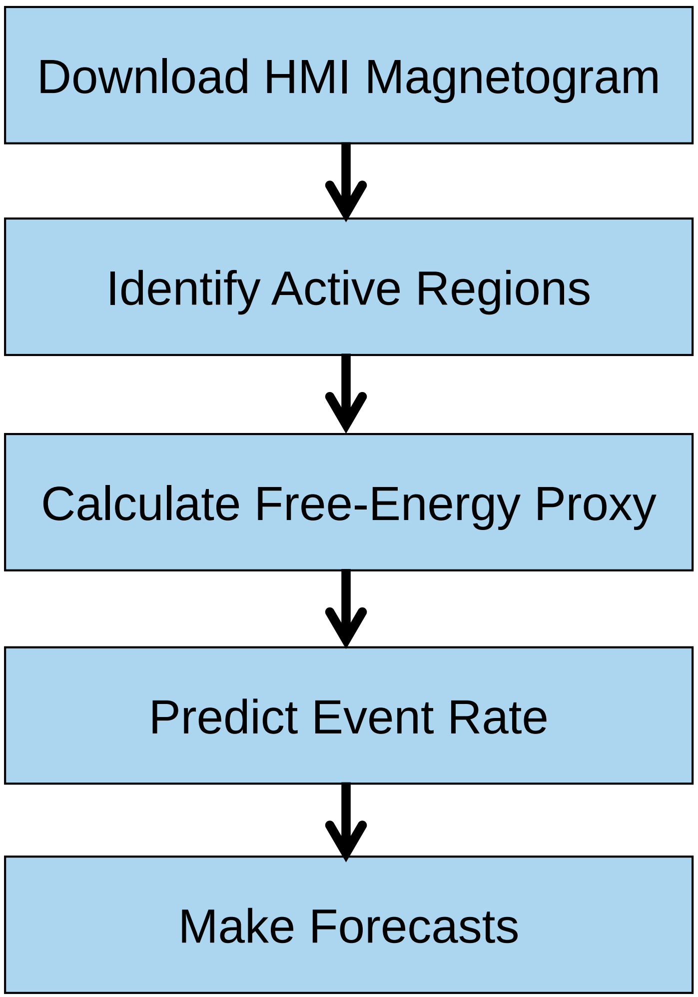
Earth magnetic field 1 G

Software Highlights

1. Automatic data downloading
2. Identifying strong-magnetic field areas
3. Associating strong-magnetic field areas with NOAA active regions
4. De-projecting vector magnetograms
5. Neutral-Line free-energy proxy
6. Associating flares in near real time, for improved forecasts
7. gentle fails
8. missing or corrupted data
9. Customizing output for various customers

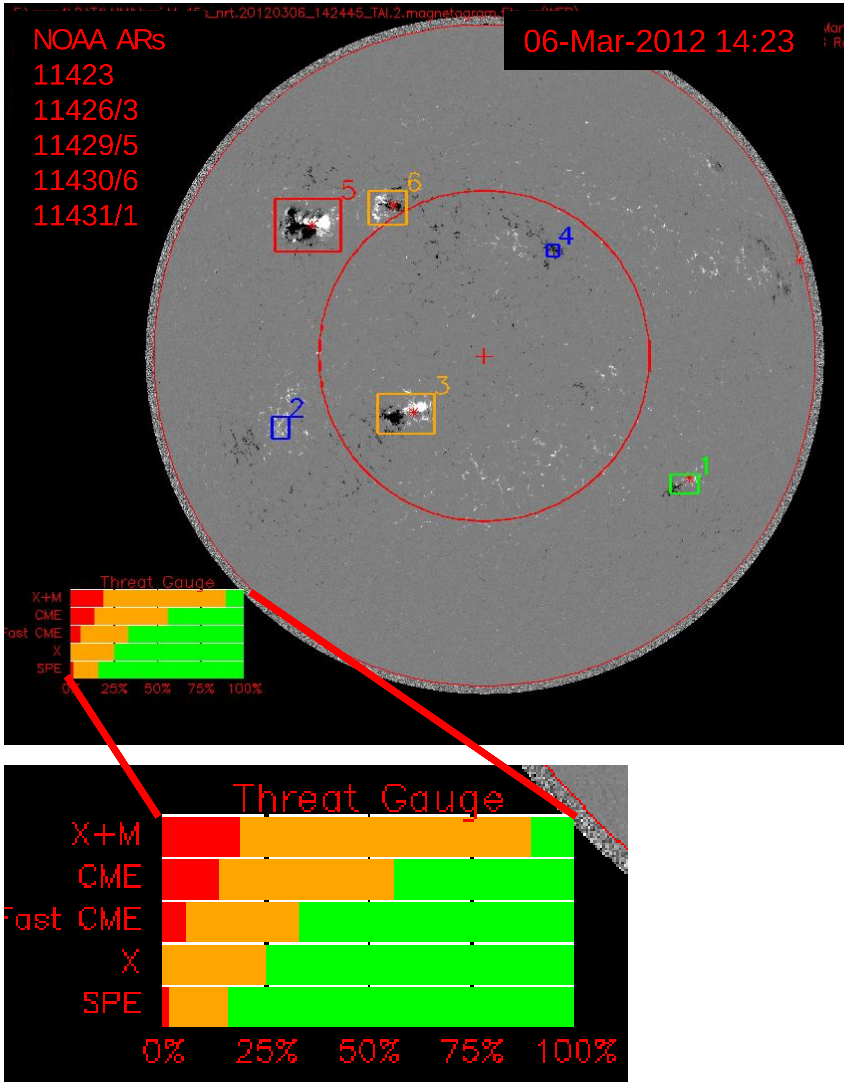


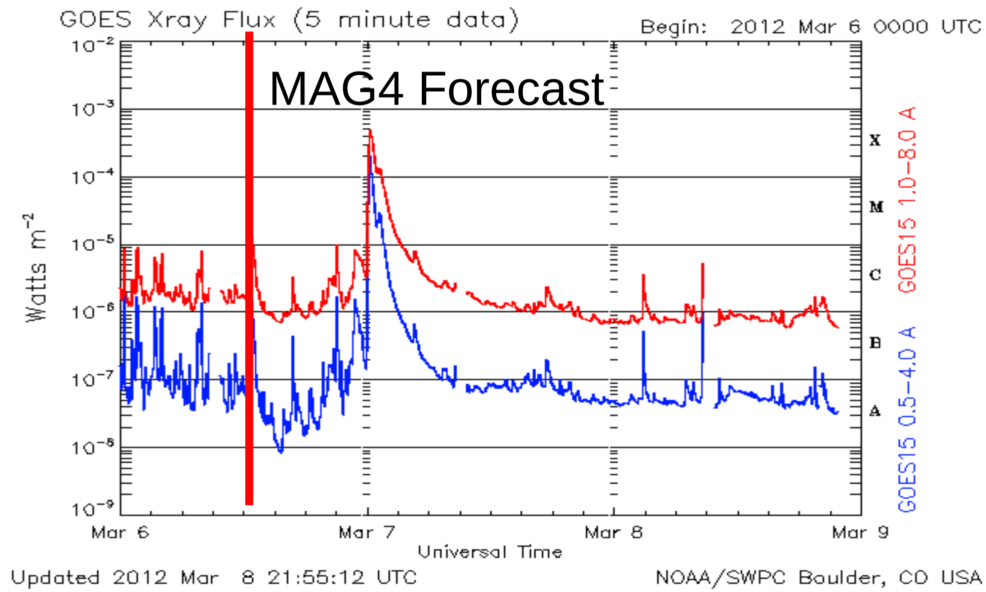
MAG4 Automated Processes



MAG4 is completely automated, from downloading magnetograms to outputting and storing forecast products

Sample Forecast

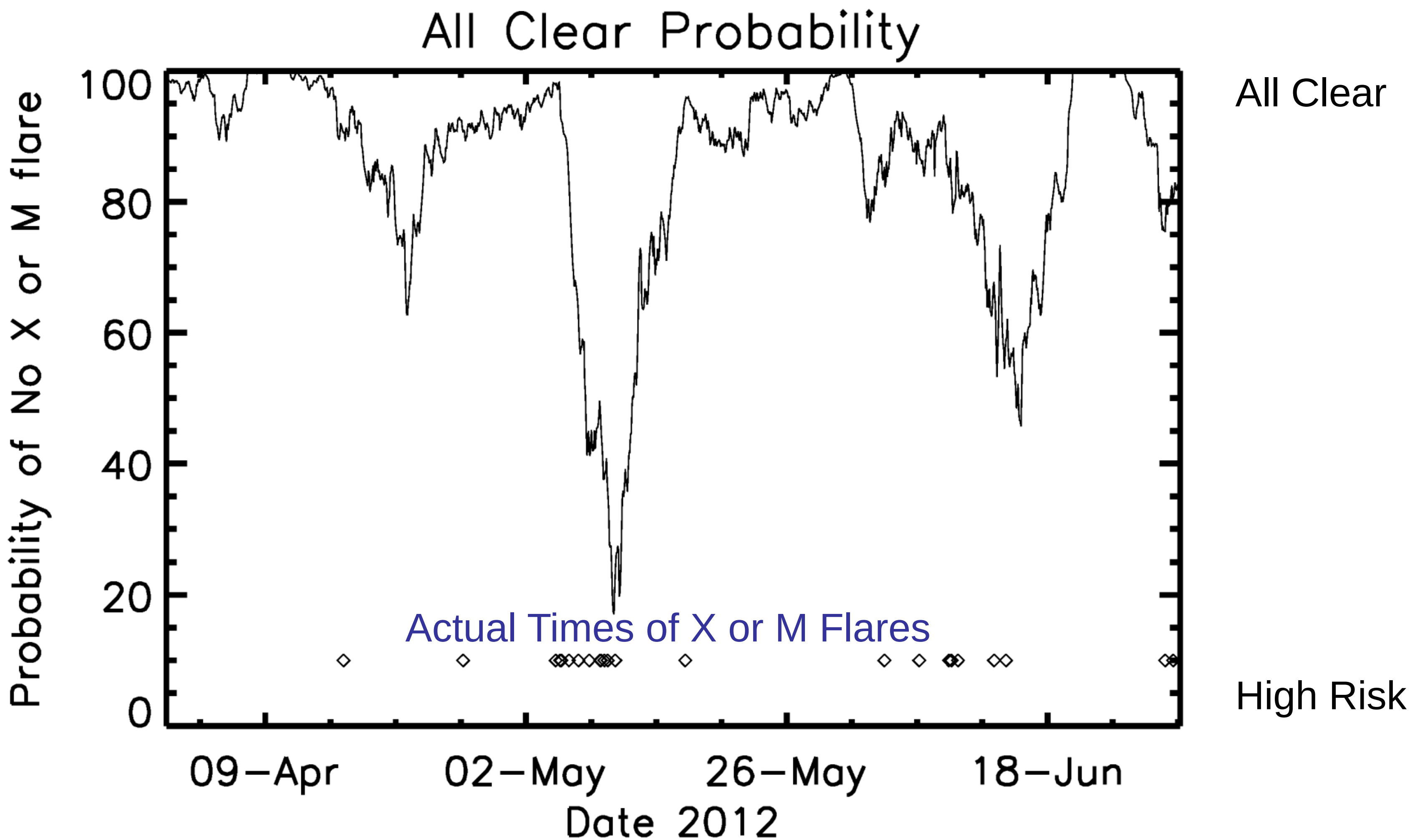




From NOAA's GOES satellite

How well does MAG4 Forecast?

Actual operational data from JSC/SRAG



MAG4 versus State of Art

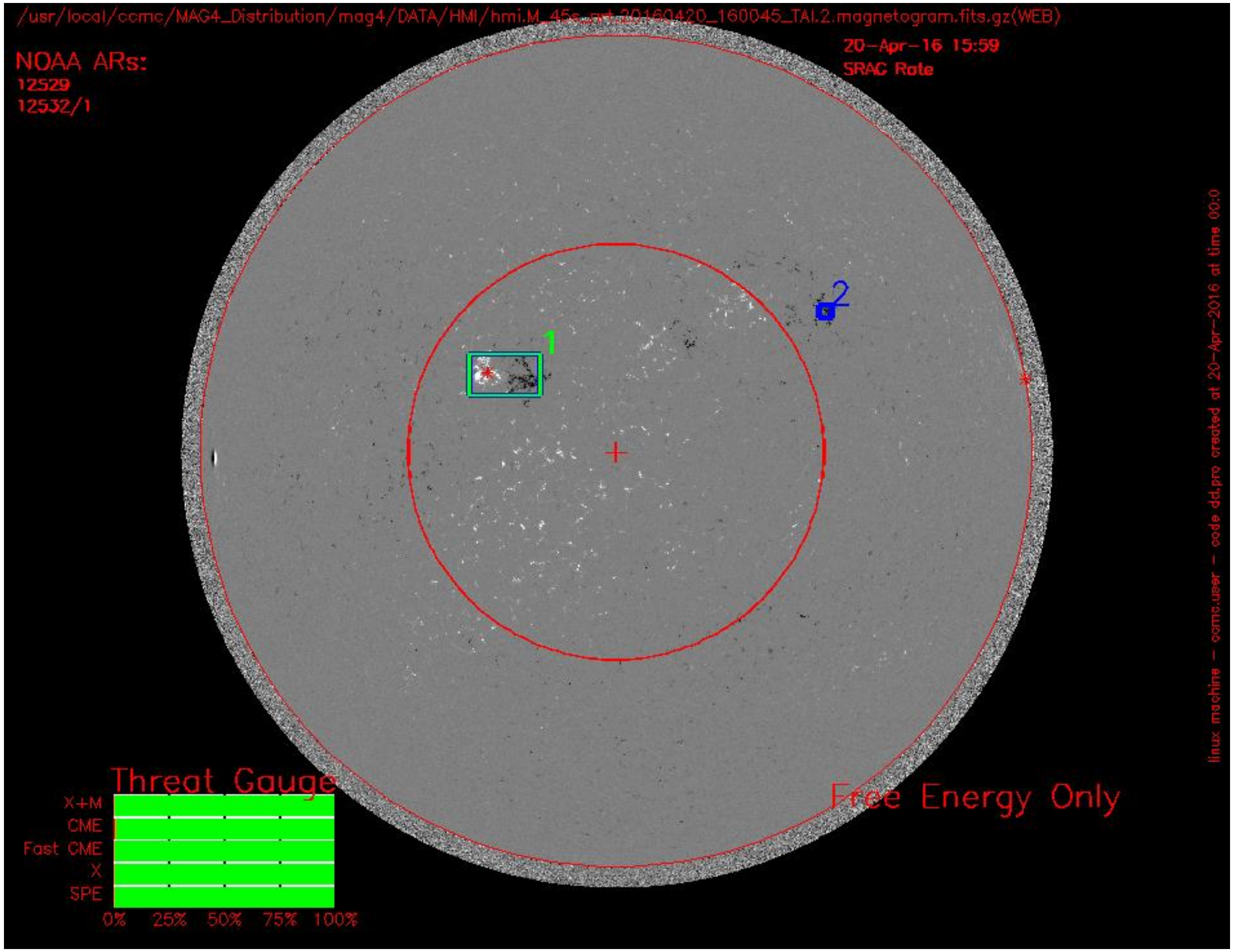
- ~~For rare events **Percent of Correct (PC)** forecast is of little use~~
- **Probability of Detection (POD)** events correctly forecasted
- **False Alarm Rates (FAR)** predicted events that did not occur

Forecast Method	POD	FAR
State of Art[1]	0.29	0.71
MAG4	**0.38**	**0.48**
Significance	**(2σ)**	**(3σ)**

[1] Input into NOAA Forecast

MAG4 Demonstration

[CCMC MAG4]



Wrap Up

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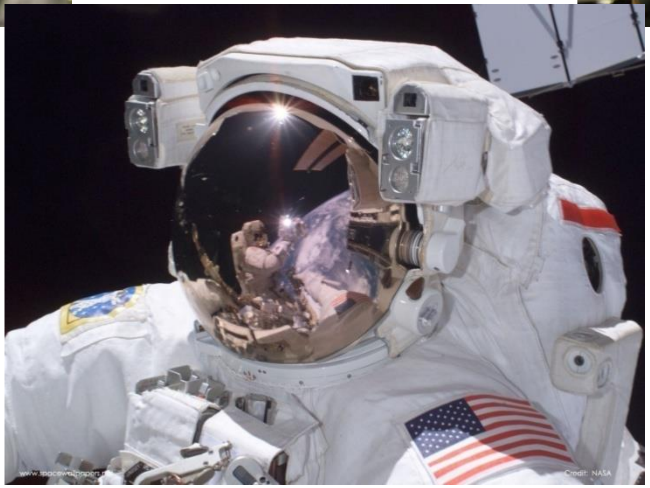
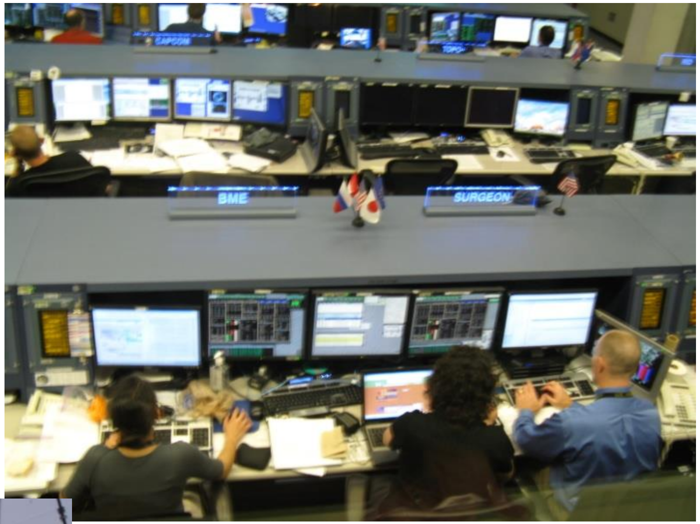
Backup Slides……………………………………………..

SRAG

EVA





Mission Control

MAG4 Computer Language and Platforms

- IDL was the language that was used for most of the development. IDL is good at array manipulation, and is the dominant language used for Solar Physics. There is an extension of IDL called SolarSoft, subroutines from there were copied and used, but since SolarSoft could be upgraded in a way that might cause problems, MAG4 is not run in the SolarSoft environment

- Java codes used as a backup tool for data retrieval at some point for a few months it was only way to get data
- PHP codes for communication with web
- A few Unix native programs fitted to be used in multi OS environment.(zip, wget, etc)

Platforms

We started with Windows, and Dr. Khazanov added other platforms as requested.

- SRAG JSC - Windows and Mac OS
- USAF - Linux and Windows
- CCMC - Linux

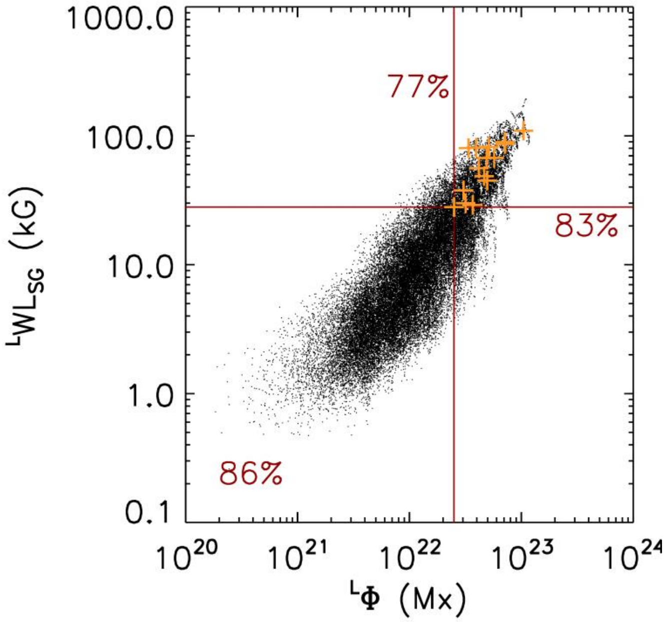
MAG4 Research-to-OperationsTimeline

- *2011* MAG4 installed at JSC Space Radiation Analysis Group (SRAG) as a <u>NRT (Near-Real-Time) forecasting tool</u>, and SRAG began pre-operations testing
- *2012* Provided NOAA web access to MAG4 NRT forecasts
- *2013* MAG4 upgraded so that it can use a combination **of free-energy proxy** and previous **flare activity, for better accuracy**
- *2013* Won the Silver Snoopy Award
- *2015* Transition from HMI line-of-sight magnetogram to vector magnetograms

Silver Snoopy
"Employees must have significantly contributed to the human space flight program to ensure flight safety and mission success."

Current and Planned Improvements for MAG4

- Continue to afford support and upgrades to JSC/SRAG
- Correct for known projection errors in free-energy proxies
- Take full advantage of vector magnetograms
- Improve All Clear Forecast for SPE
- Partner with Air Force, and NOAA

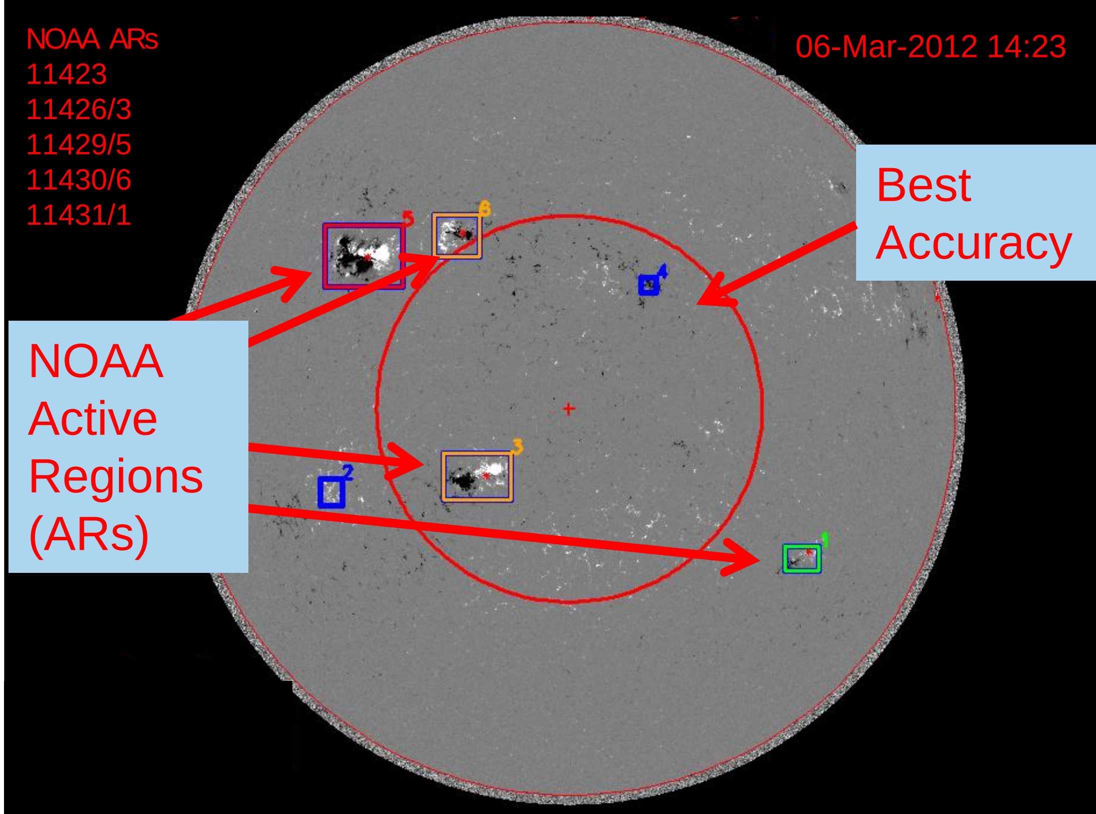


The gold crosses represent active regions that produce an SPE while the black dots do not.

Identifying Active Regions on the Sun

- Magnetograms are spatial maps of the magnetic field strengths
- They come in two basic types
  - line-of-sight (right)
  - vector magnetograms
- Free-energy proxies can be measured for Active Regions (areas with sunspots) from either type of magnetogram
- Line-of-sight magnetograms suffer reduced accuracy further from disk center

Magnetograms & identify active regions



A full-disk line-of-sight magnetogram of the Sun, from SDO/HMI.

How Well Does MAG4 Forecast:

2. Skill Metrics Significance of Upgrade

Forecast Method	YY	YN	NY	NN	PC(%)	POD	FAR	HSS	TSS
McIntosh/**NOAA**	259	638	631	18476	93.7	0.29	0.71	0.26	0.26
Free-Energy Proxy **Present MAG4**	273	284	618	18830	95.5	0.31	0.50	0.35	0.47
Free-energy proxy and previous flare activity **Upgraded MAG4**	340	317	551	18797	**95.7**	**0.38**	**0.48**	**0.42**	**0.49**
Best	890	0	0	1911 4	100	1	0	1	1

Improvement in Metric	PC(%)	POD	FAR	HSS	TSS
McIntosh/**NOAA** **Present MAG4**	1.8±0.5 **(4σ)**	0.03±0.05 **(0.3σ)**	0.21±0.07 **(3σ)**	0.10±0.04 **(2σ)**	0.21±0.07 **(3σ)**
Present MAG4 Upgraded MAG4	0.2±0.2 **(0.7σ)**	0.08±0.03 **(2σ)**	0.02±0.05 **(0.5σ)**	0.06±0.03 **(2σ)**	0.03±0.05 **(0.5σ)**

How Well Does MAG4 Forecast:

2. Skill Metrics Equations

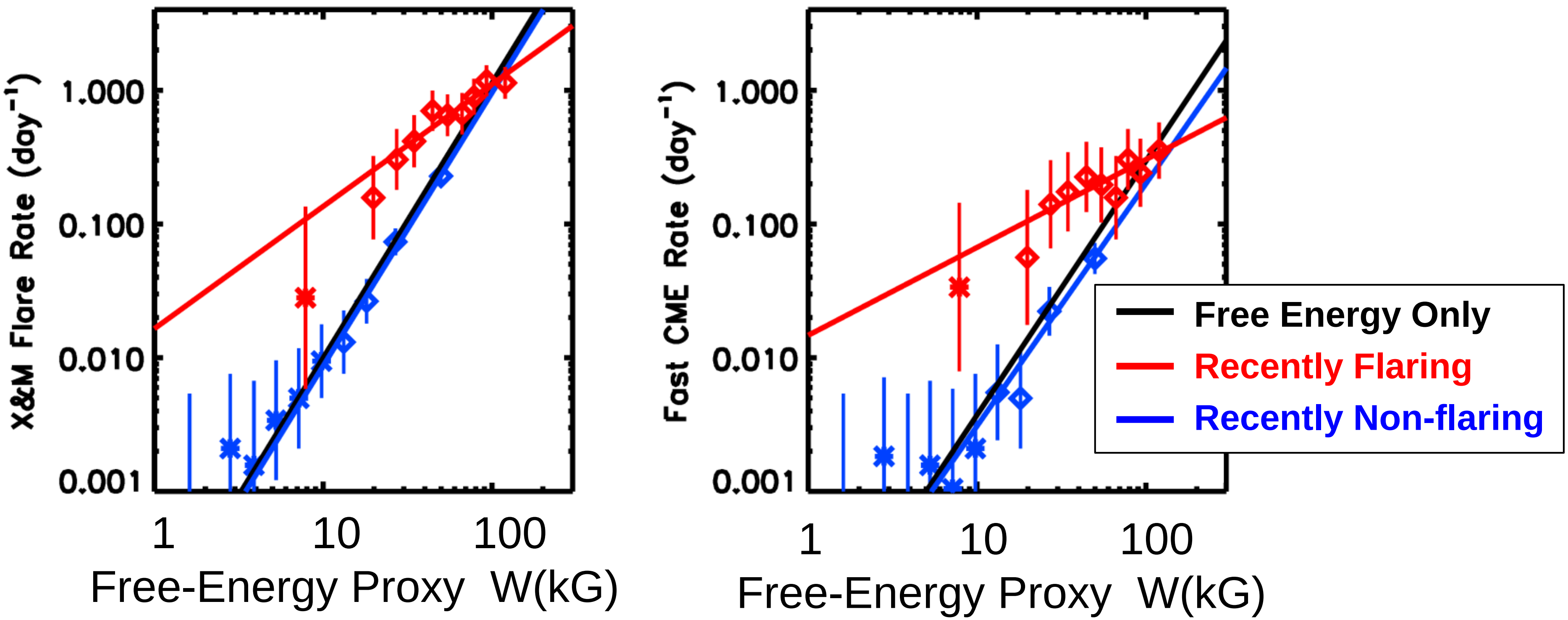
	Actual Yes	Actual No
Predict Yes	YY	YN
Predict No	NY	NN

Metric Equations

Percent Correct	PC=(YY+NN)/(YY+YN+NY+YY)
Probability of Detection	POD=YY/(YY+NY)
False Alarm Rate	FAR=YN/(YY+YN)
Heidke Skill Score	HSS=2*(YY*NN-YN*NY)/[(YY+NY)*(NY+NN)+(YY+YN)*(YN+NN)]
True Skill Score	TSS=(YY*NN-NY*YN)/((YY+NY)*(YN+NN))

Improving the Forecasts:

1. Recent Flare History (In Progress)

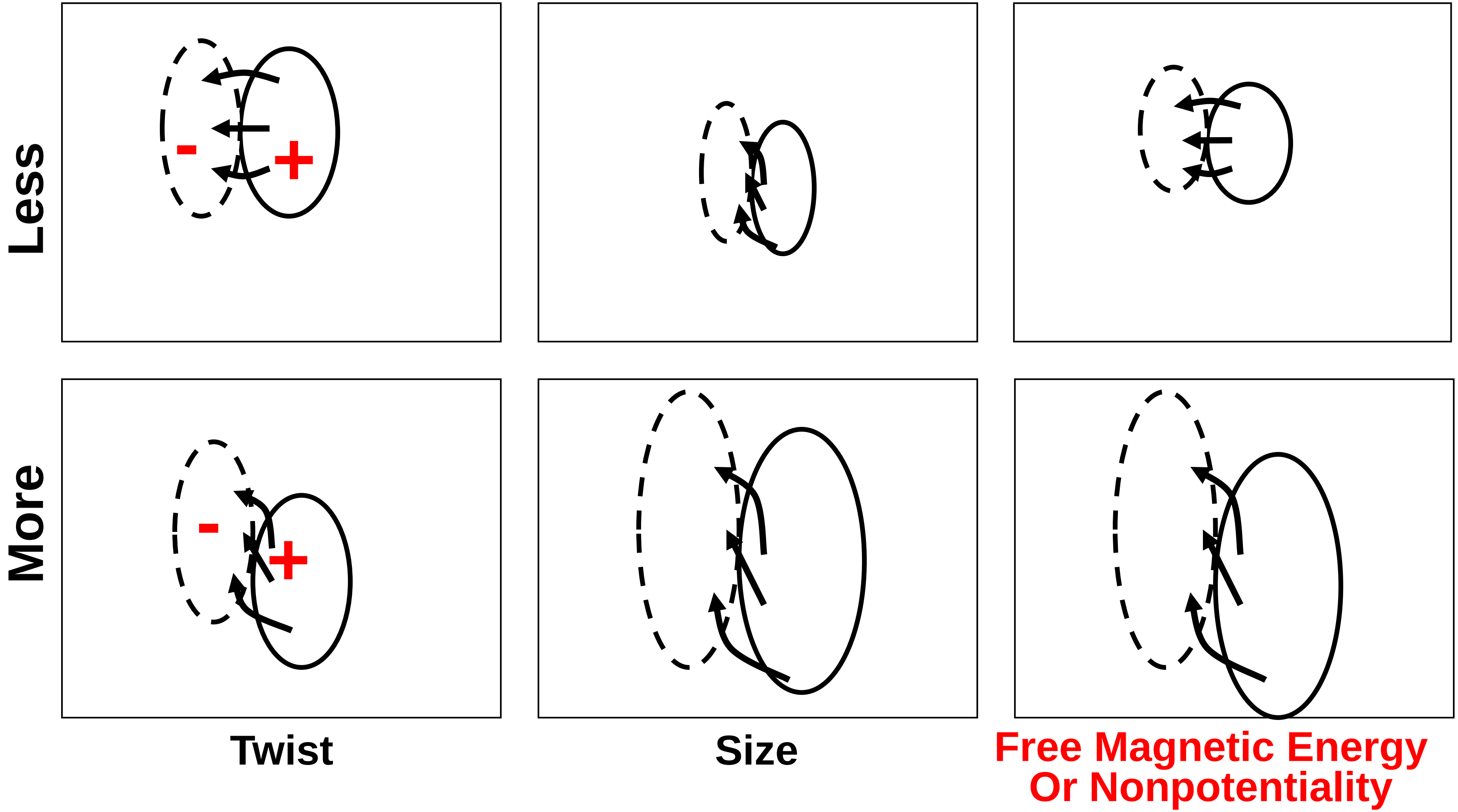


Active regions that have recently produced an X- or M-Class flare are more likely to produce flares in the near future

Free-Magnetic Energy

Contours Vertical Magnetic Field
Arrows Transverse Magnetic Field

Currents ~10^{12} Amps



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Comparison of Safe and Not Safe Days

June 26, 2013

C1, C1.5 flares

March 7, 2012

X5.4, X1.3, C1.6

CME 2684, 1825 km/sec,

Solar Energetic Proton Event reaches 6530 particle flux unit >10MeV