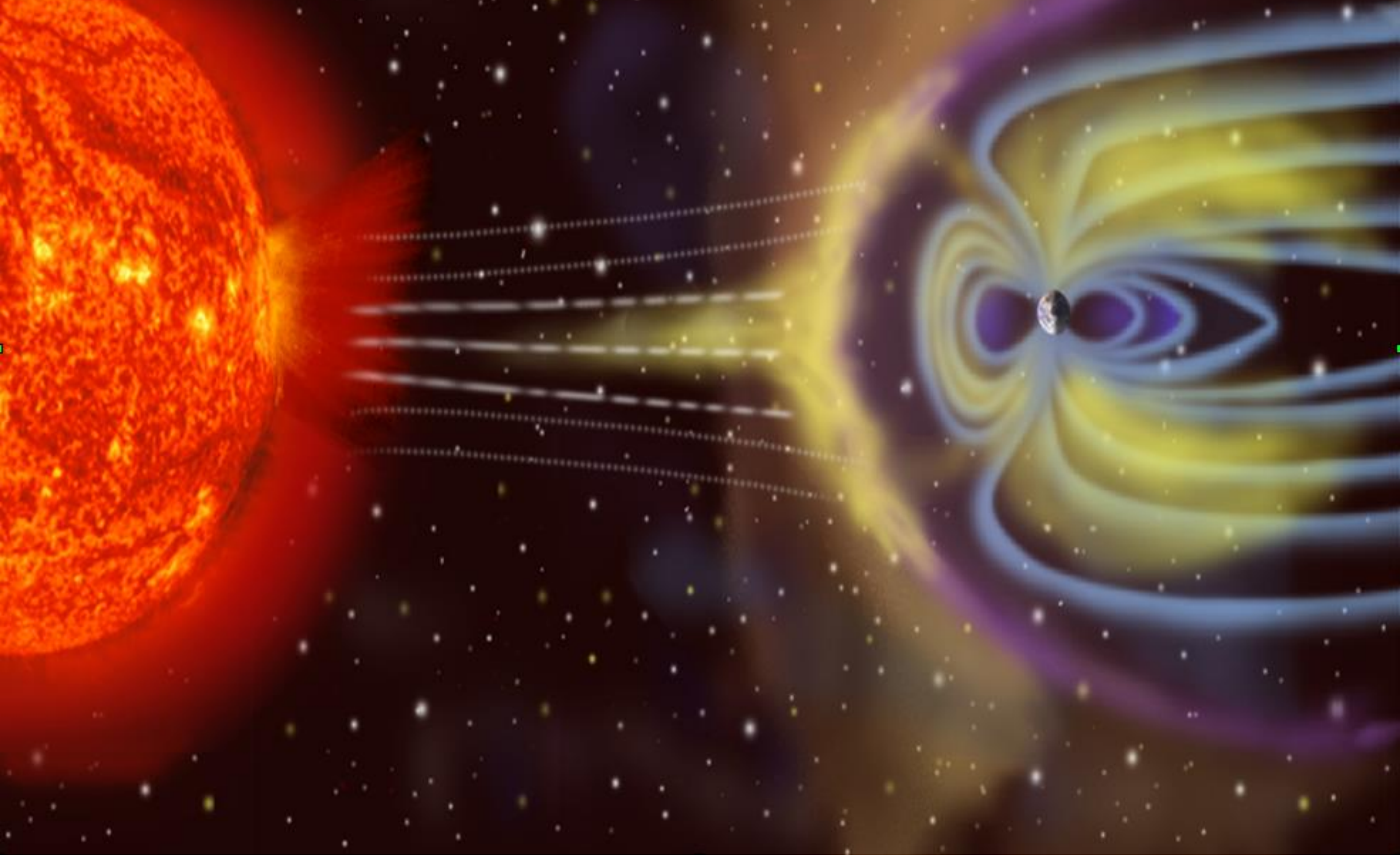
Active Regions, Flare and CMEs: Drivers of Severe Space Weather

David Falconer



Outline

- **The Threat of Space Weather**
- The Science
- Research too Operations (R2O)

Drivers of Severe Space Weather

Can affect

- Astronauts
- Satellites
- Communication
- GPS
- Airline polar flights
- Power grids

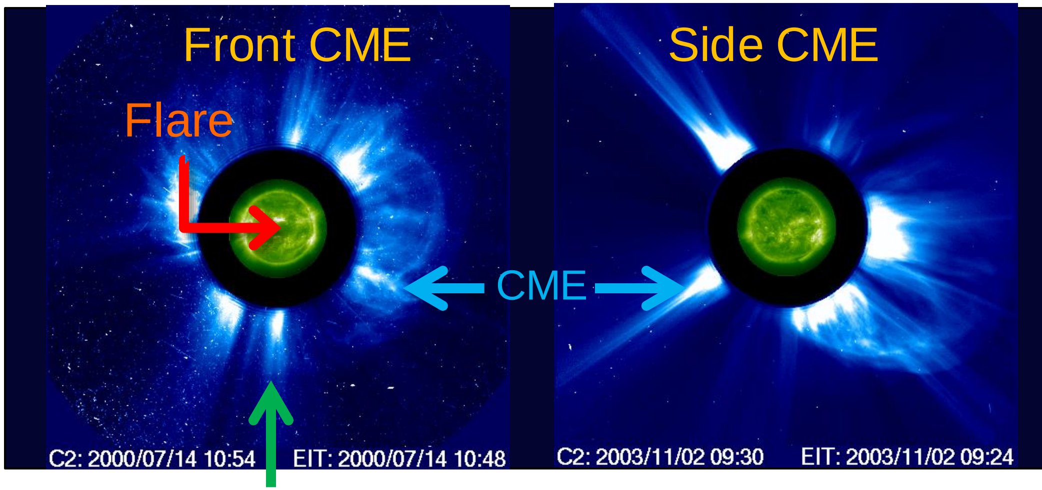
Animation of flare and co-produced CME that creates a geo-magnetic storm.

Animation from NASA/Goddard Space Flight Center Conceptual Image Lab: https://svs.gsfc.nasa.gov/20057

Various Forms of Severe Space Weather

Dangerous space weather is driven by solar flares and Coronal Mass Ejection (CMEs).

Forecasting flares and CMEs is the first step to forecasting either dangerous space weather or All Clear.



Space Weather

Flare

ELECTROMAGNETIC RADIATION
(IMMEDIATE: TIME 8 MIN)

- X-EUV
- ULTRA-VIOLET
- VISIBLE LIGHT
- RADIO WAVES

SIMULTANEOUS EFFECTS

- INCREASED D-LAYER IONIZATION
  - GEOMAGNETIC DISTURBANCE
  - ANOMALOUS RADIO PROPAGATION
- OUTBURST OF RADIO NOISE
  - RADIO INTERFERENCE

Solar Energetic Particle Event (SPE or SEP Event)

HIGH ENERGY PARTICLES
(DELAYED < HOUR)

- ATOMIC NUCLEI

CME

ENHANCED SOLAR WIND
(DELAYED ~1-3 Days)

- IONS AND ELECTRONS

DELAYED EFFECTS

- ENHANCED ENERGETIC PARTICLES
  - MANNED FLIGHT RADIATION HAZARD(I)
  - SPACECRAFT RADIATION HAZARD (C^3)
- IONIZATION
  - ANOMALOUS RADIO PROPAGATION
  - RADAR CLUTTER
- GEOMAGNETIC STORM
  - IONOSPHERIC STORM AND
  - INDUCED CURRENTS
  - RADIO EFFECTS
  - SATELLITE DRAG
  - AURORA

S.T. Wu

Human Space Flight

Shuttle missions and Extra-Vehicular Activity require particular attention. The Space Radiation Analysis Group (SRAG) continuously monitors space weather and reports to the Flight Surgeon, if there is a problem or if there is a likelihood of a problem.

SRAG/
Johnson Space Center

Mission Control/
Johnson Space Center

EVA

Satellite Radiation Damage

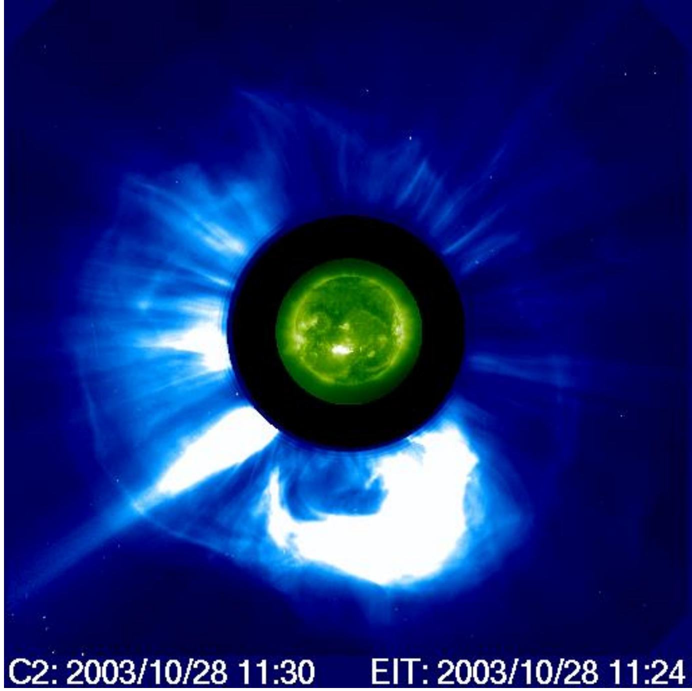
Particle Radiation produced by coronal mass ejections and flares can damage electronics on satellites.

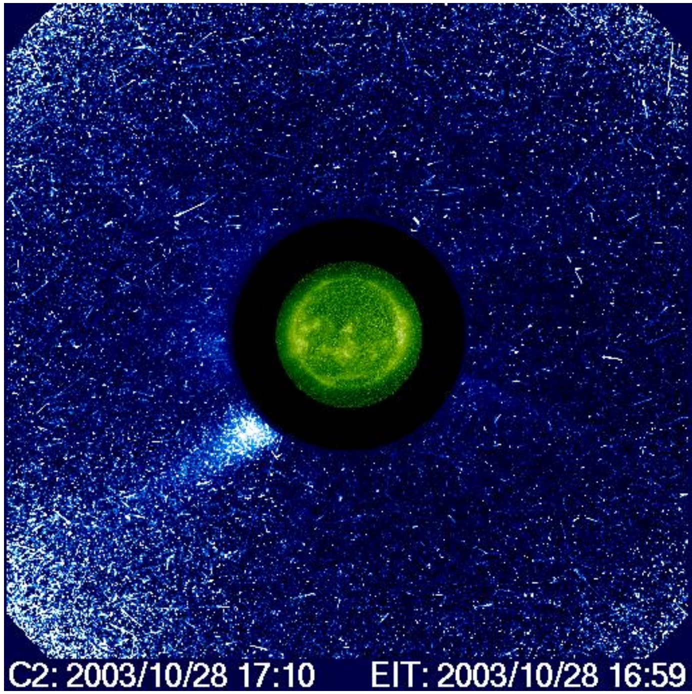
- 1991 GOES
- 1995 Deutsche Telekom
- 1996 Telesat Canada
- 1997 Telstar 401
- 2000/07/14 ASCA
- 2003 Mars Odyssey

- 4500 spacecraft anomalies over last 25 years

- A big event could cause billions of dollars in damage

GOES





SOlar and Heliospheric Observatory (SOHO)
Blue: LASCO
Green: EIT

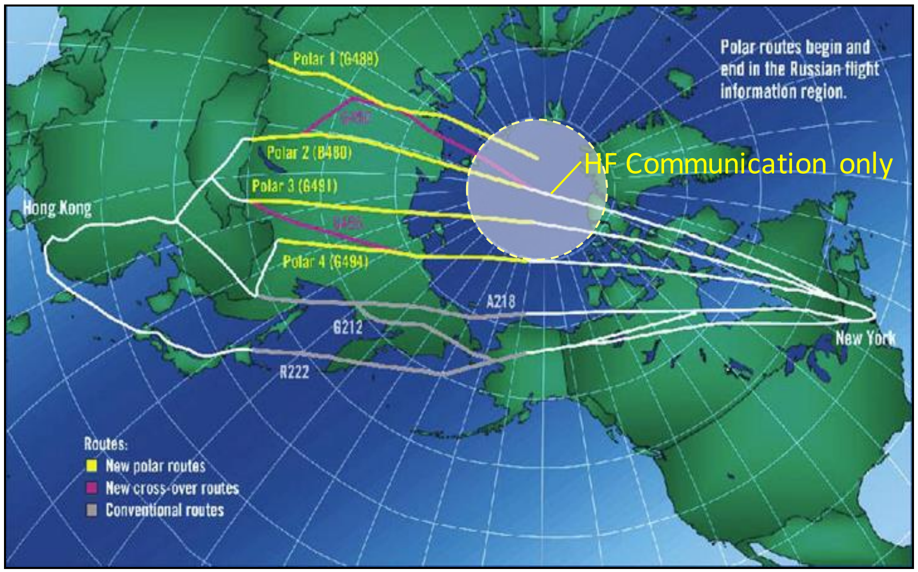
Satellite Drag

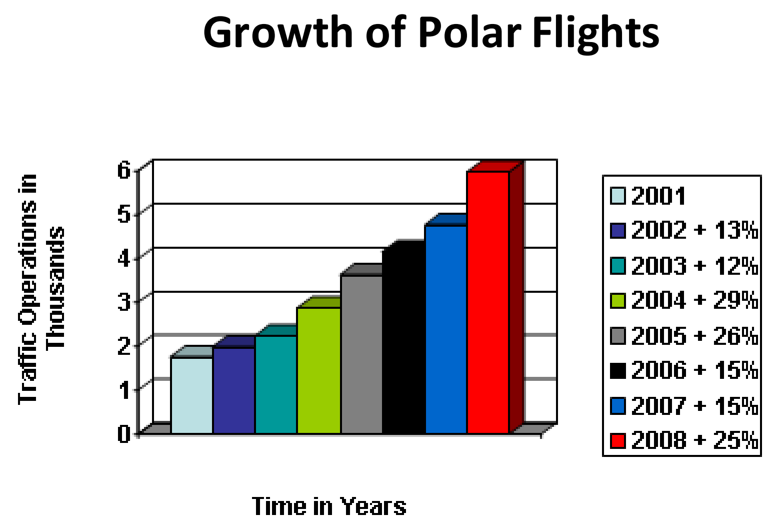
- Variations in the Sun's UV and EUV irradiance over a solar cycle produce factors of 10 changes in the density at some spacecraft altitudes.
- Geo-Magnetic storms can produce larger, but shorter term variations.
- The increase drag can bring satellites down quicker
- The increase drag also shifts the orbit of space junk, requiring the U.S. Space Command to predict the change, and re-determine orbits.

People at NOAA, and scientists who study the magnetosphere and upper atmosphere need improved CME forecasting to improve the science of forecasting the neutral atmospheric density, and thus satellite drag.

NASDA (National Space development Agency of Japan)

Airline Polar Flights





NOAA SWPC images

- Loss of Communication
- Loss or degradation of GPS (especially important for landings)
- Increased Radiation Levels

Power Grids

Catastrophic Damage: A Modern Carrington Level Event

Lesser Event

Major Damage

"This image shows heating related damage to the current carrying windings of the transformer. To provide cooling for normal operations, the coils are immersed in an oil-bath. As you can see, an oil-bath does not cool well enough to protect against the GIC."

Damaged Power Station Transformer

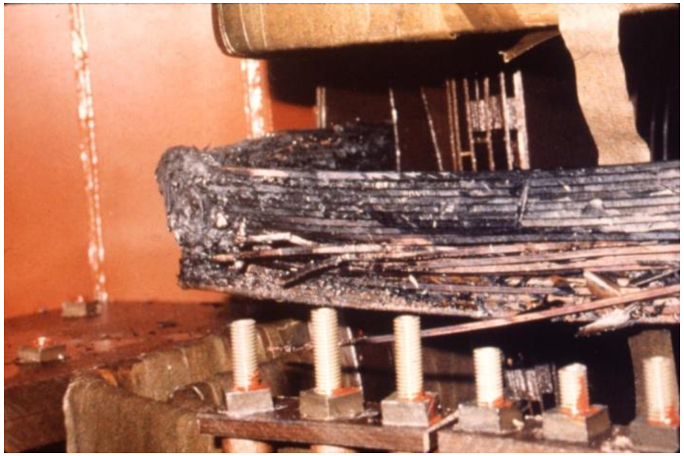


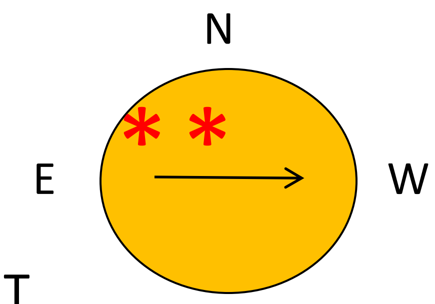
Image from J.G. Kappenman

March 1989 Quebec Blackout

On March 13, 1989 the entire province of Quebec, Canada suffered an electrical power blackout.

March 1989 Quebec Blackout

- AR 5395 produced on March 6, 14UT a X15 flare N35E69
- March 10 18UT a X4.5 flare N35E14
- Geomagnetic event starts on March 12.
- Reaches a DST -589 on March 13 1UT
  - largest DST magnitude in last 50 years. March 13, 7:44 UT Quebec Blackout



"On the evening of Monday, March 12 the vast cloud of solar plasma (a gas of electrically charged particles) finally struck Earth's magnetic field. The violence of this 'geomagnetic storm' caused spectacular **'northern lights' that could be seen as far south as Florida and Cuba**. The magnetic disturbance was incredibly intense. It actually created electrical currents in the ground beneath much of North America. Just after 2:44 a.m. on March 13, the currents found a weakness in the electrical power grid of Quebec. In less than 2 minutes, the entire Quebec power grid lost power." ***Dr. Sten Odenwald***

Space Weather Forecasters

NOAA SWPC
(Space Weather Prediction Center)
Boulder, Co

Air Force AFWA
(Air Force Weather Agency)
Omaha, Ne

Outline

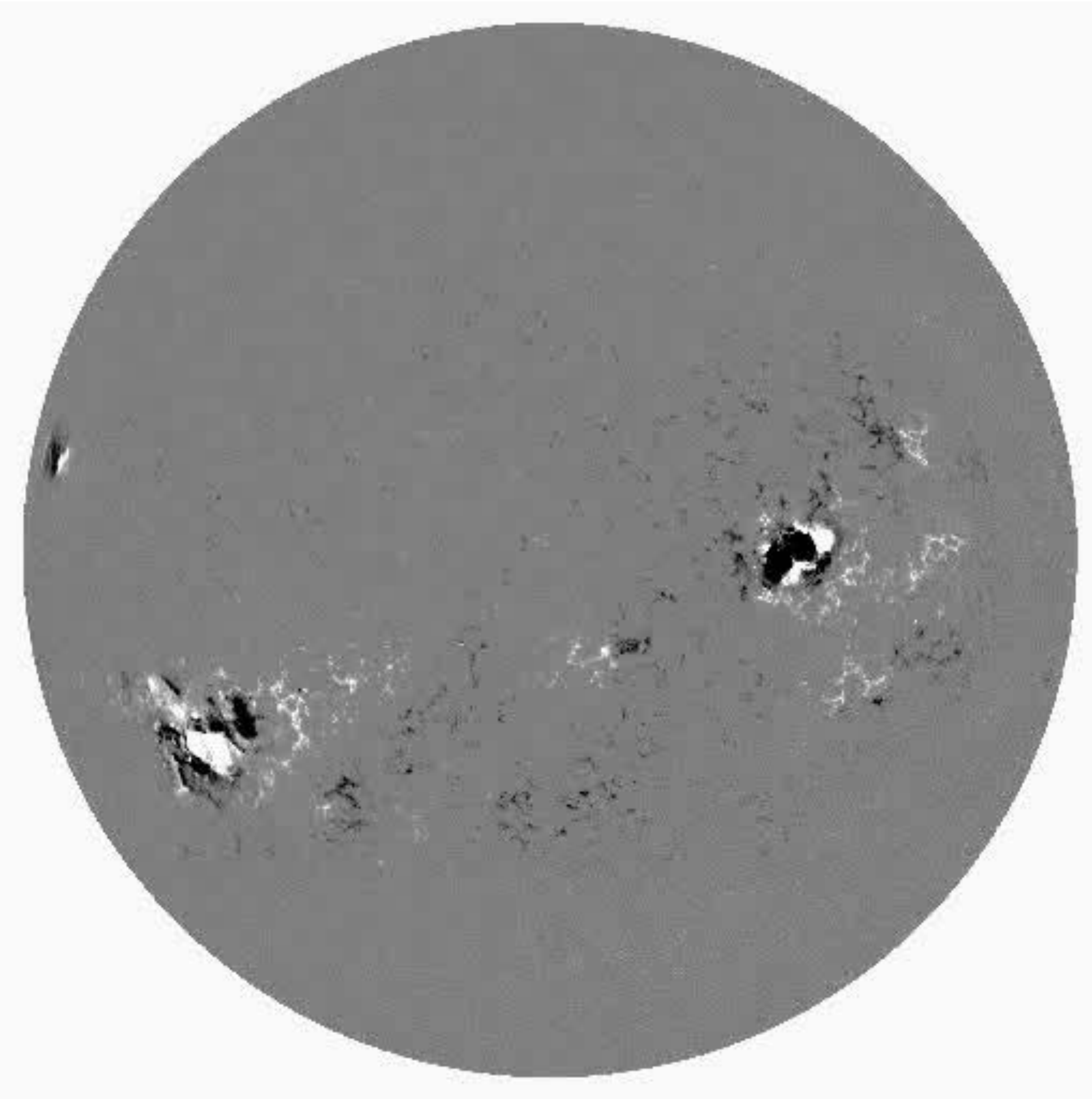
- The Threat of Space Weather
- **The Science**
- Research too Operations (R2O)

Emergence of Active Regions

Useful site
magnetograph.**msfc**.nasa.gov/

- Sunspots are on size scale of Earth
- They can have several KG magnetic field
- The example to the left is a rapid emerging AR, with two larger ones already on disk

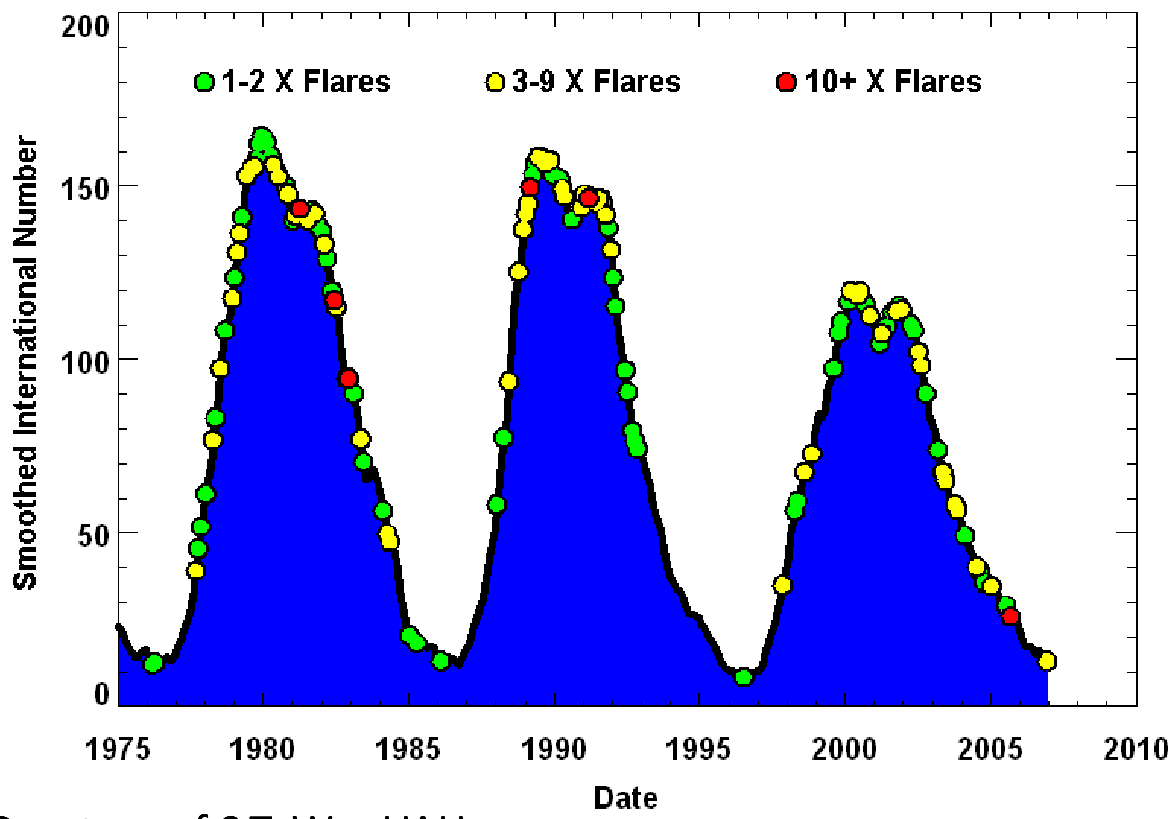
- Oct 26- Nov 3, 2003



, Movie made by David Hathaway NASA

Flares over the Solar Cycle

Solar flares have been monitored by x-ray detectors on NOAA's GOES satellites since 1976. They are classified by how bright they are in x-rays. X-Class flares are the brightest and are produced by the greatest magnetic explosions in active regions. The number of X-Class flares per month increases with the number of sunspots but big flares can occur anytime sunspots are present.



Courtesy of S.T. Wu, UAH

Magnetic Field Measuring Instruments

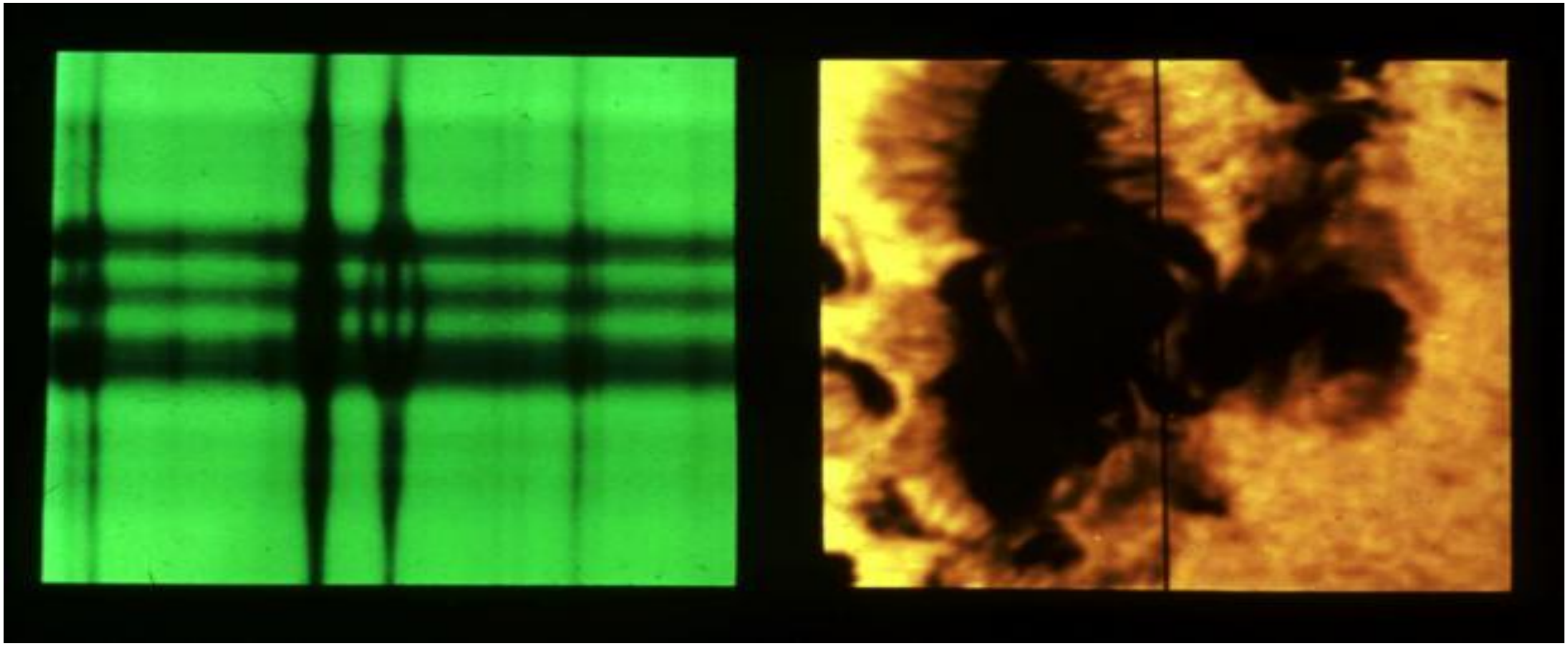
The Marshall Space Flight Center Magnetograph Facility

https://magnetograph.msfc.nasa.gov/

Measuring Magnetic Fields

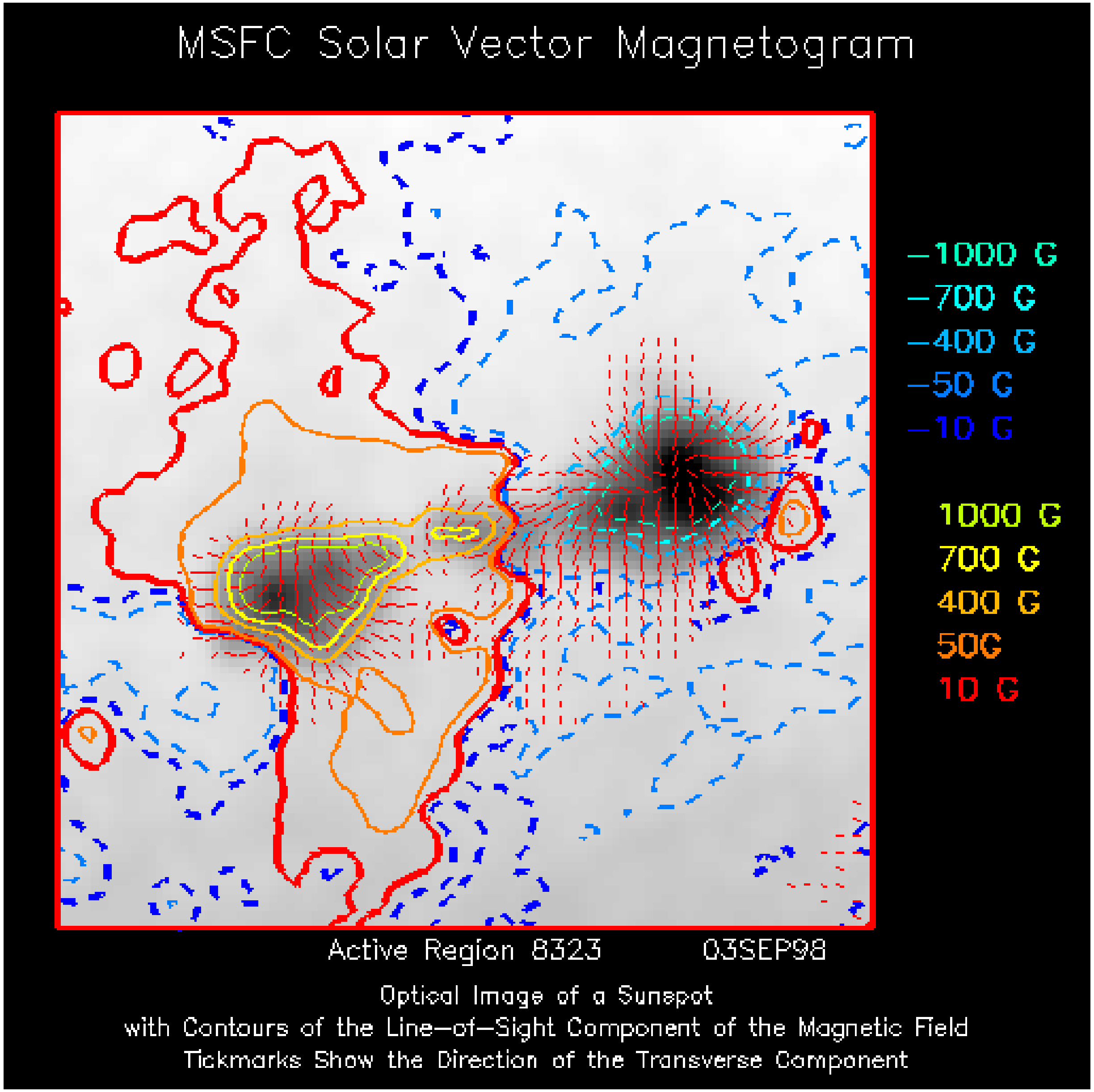
The Solar Spectrum

The Zeeman Effect



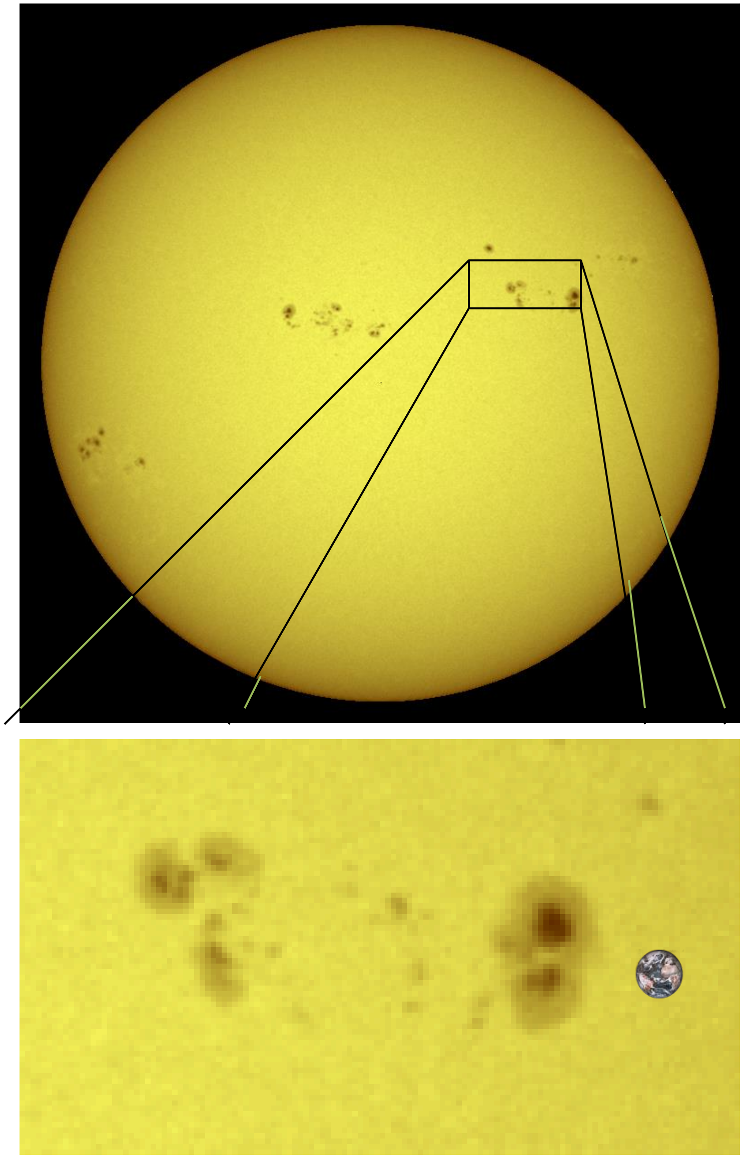
https://magnetograph.msfc.nasa.gov/magmore.shtml

Magnetic Fields in Sunspots



NASA/MSFC vector magnetogram

Severe Space Weather is driven by CMEs and Flares Produced by Active Regions

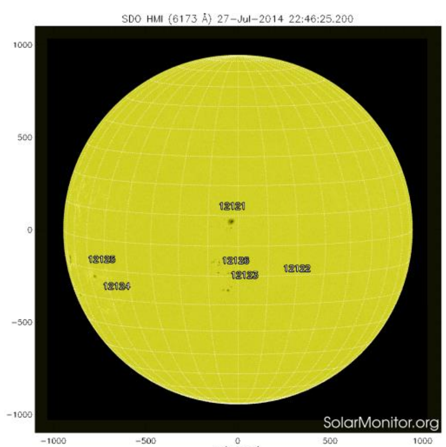


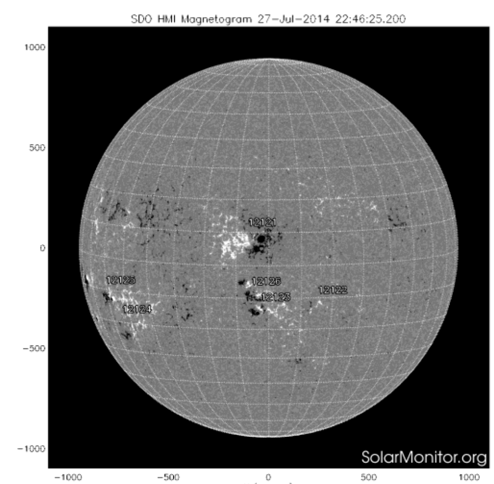
Active regions are areas that have strong magnetic fields.

Where the magnetic fields are strongest, sunspots occur.

The sunspots can be as large as the Earth.

Energy that is stored in the magnetic field can be rapidly released in an explosion that produces a CME and flare.





https://www.solarmonitor.org/

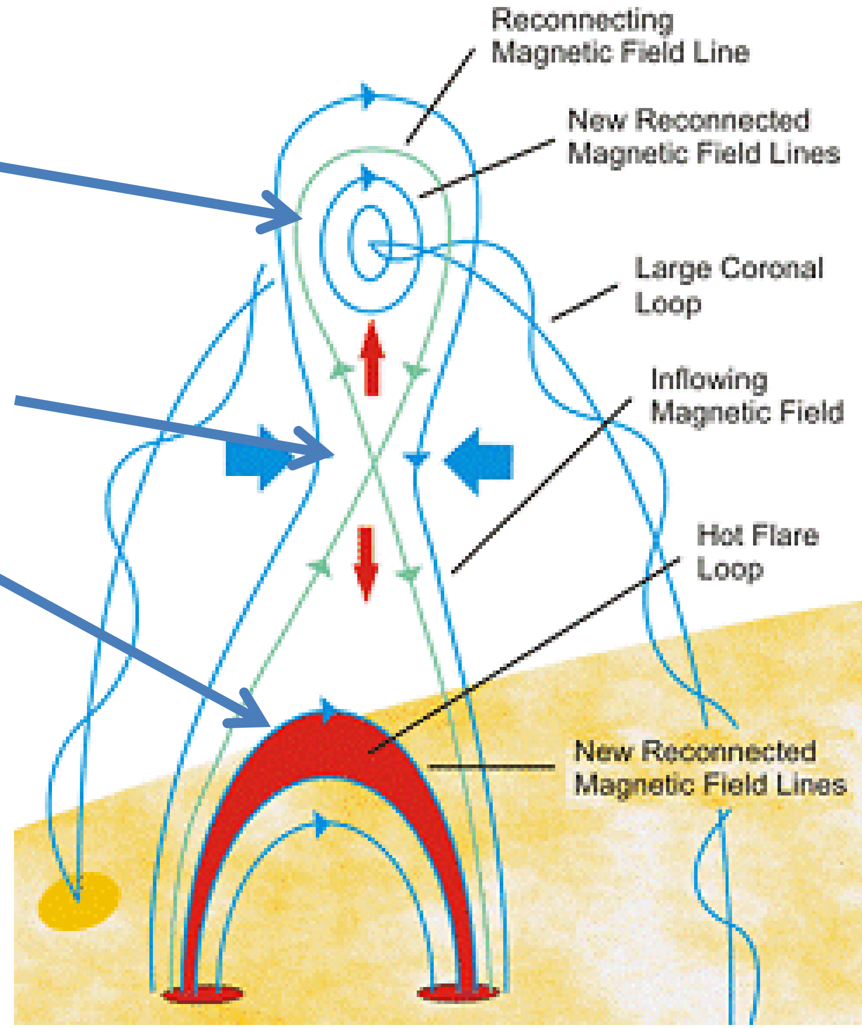
Standard Flare Model

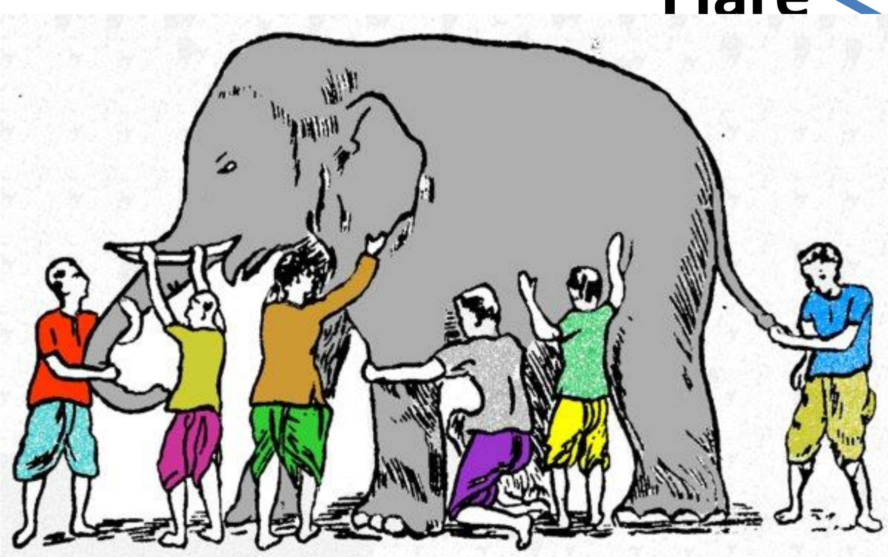
Eruptive Flare

CME

Reconnection

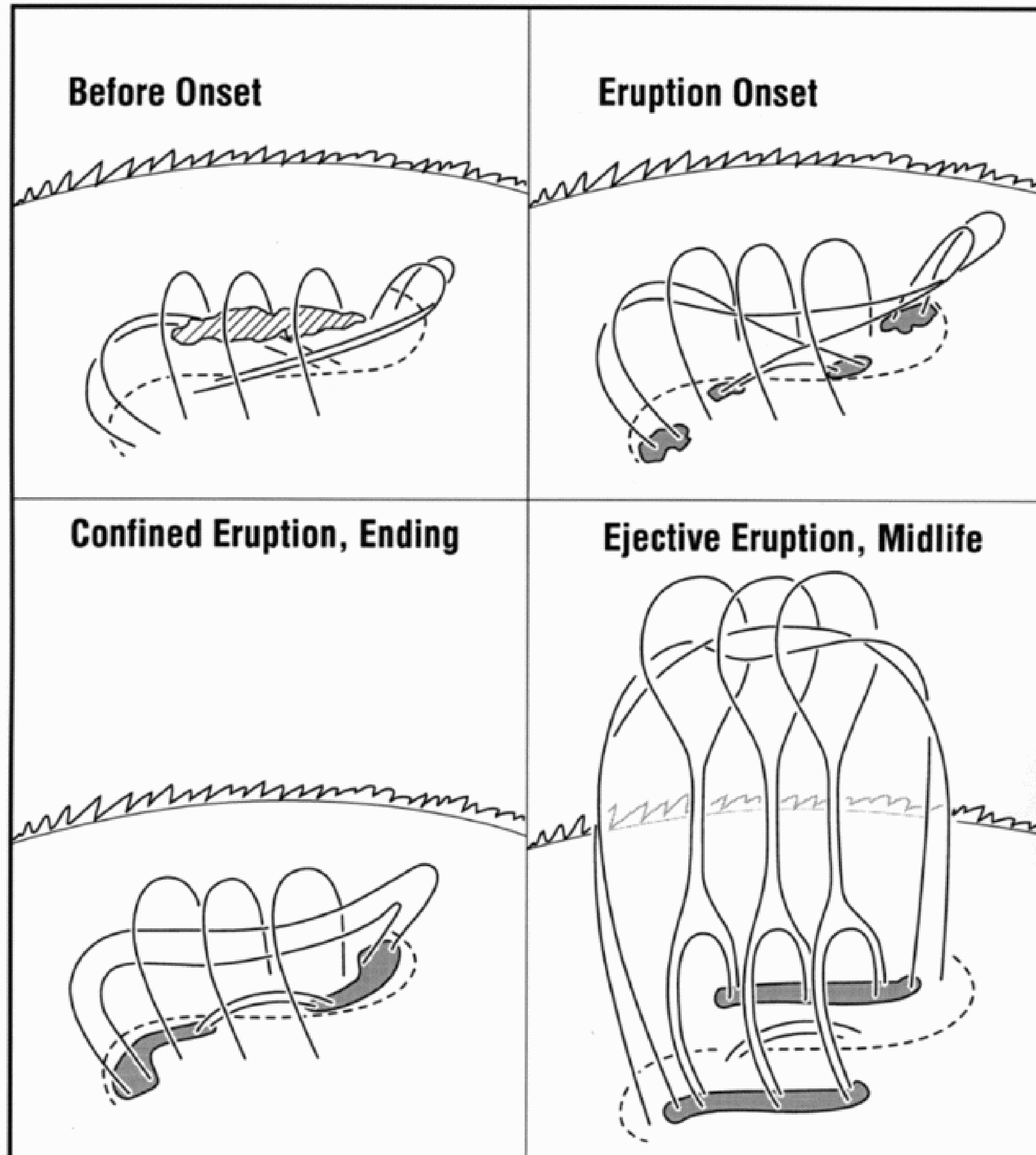
Flare





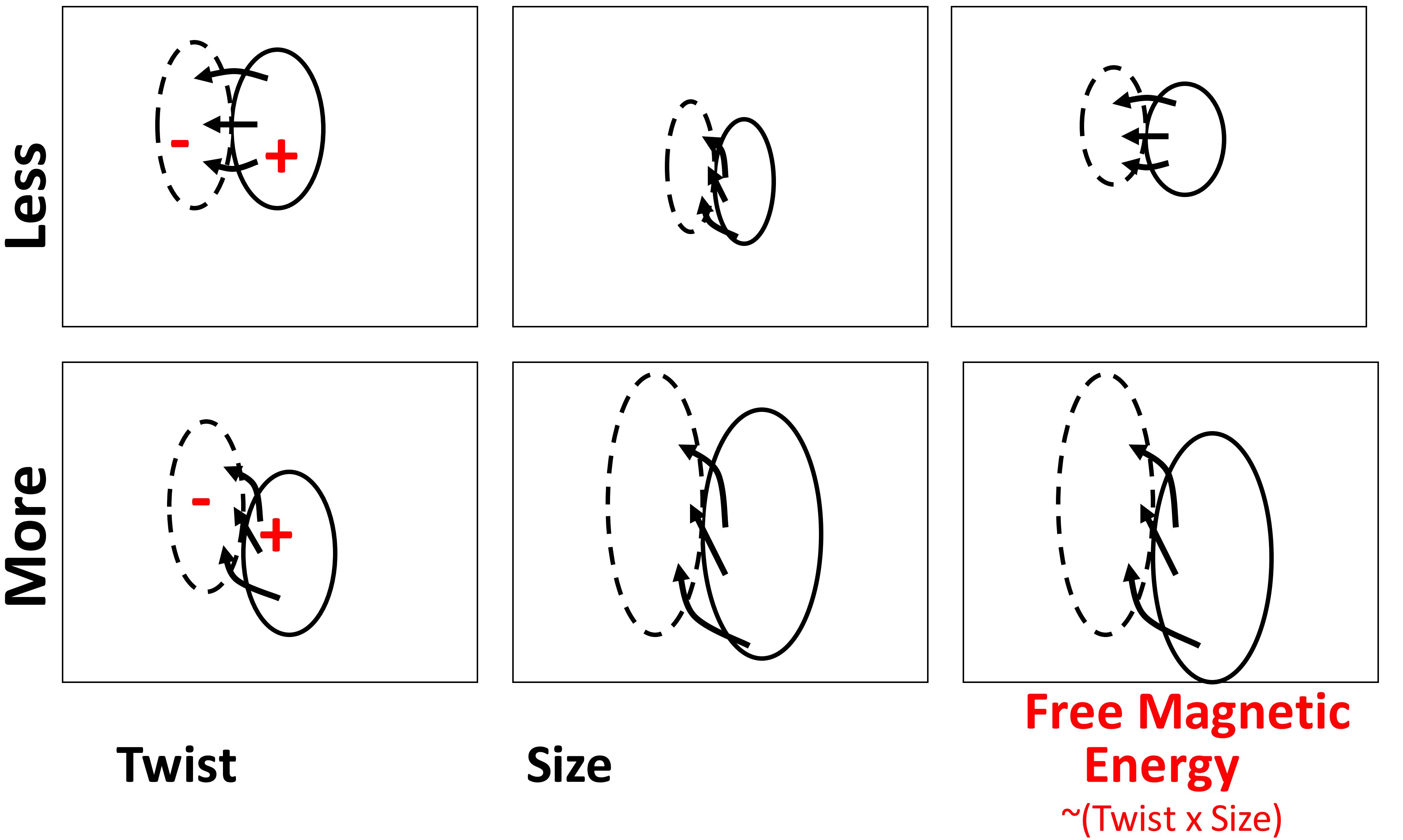
Tether Cutting CME Model

- The magnetic field starts in a stress configuration
- Magnetic reconnection occurs
- CME erupts
- The magnetic field ends in a less stress configuration
- Typically only a few percent of the magnetic free energy is released
- Minor changes to photospheric vector magnetograms

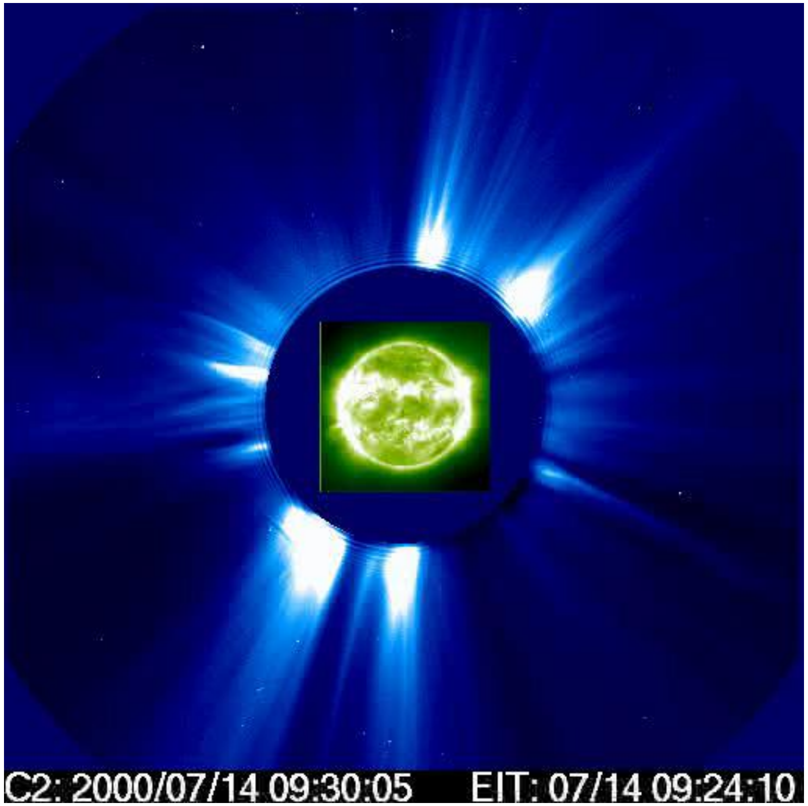


Ron Moore, NASA

Relation between Size, Twist, and Free Energy of an Active Region's Magnetic Field



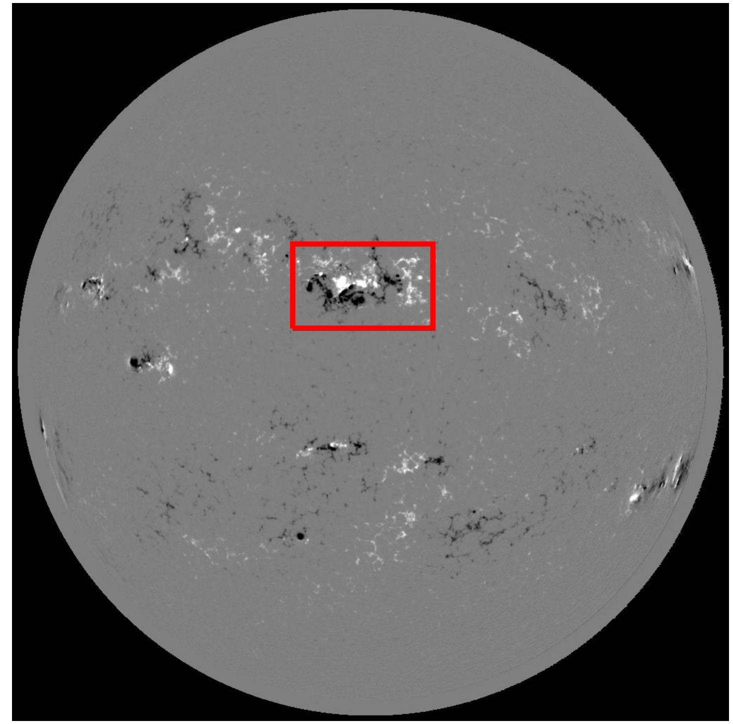
Flare/CME sources

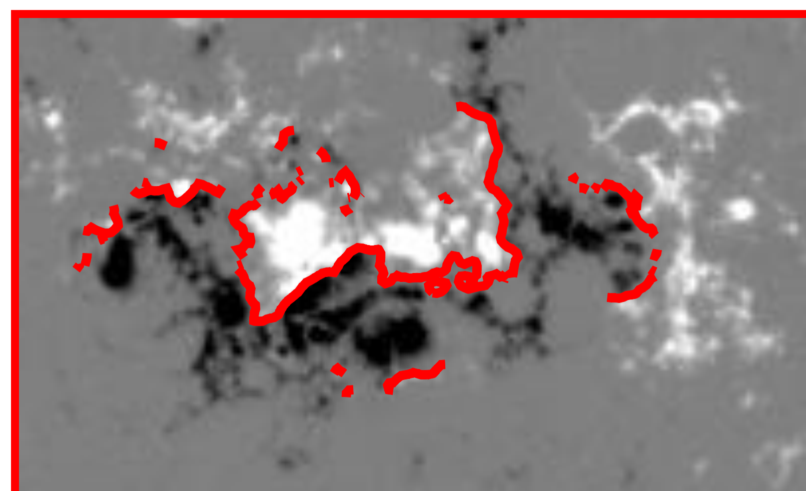


From SOHO/LASCO

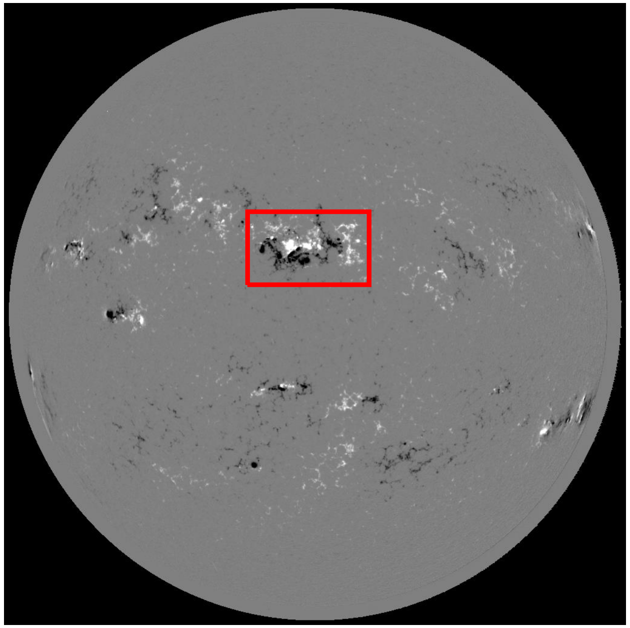
Movie of an active-region magnetic explosion that produced a Flare, Coronal Mass Ejection (CME), and Solar Energetic Particle Event (SEP event).

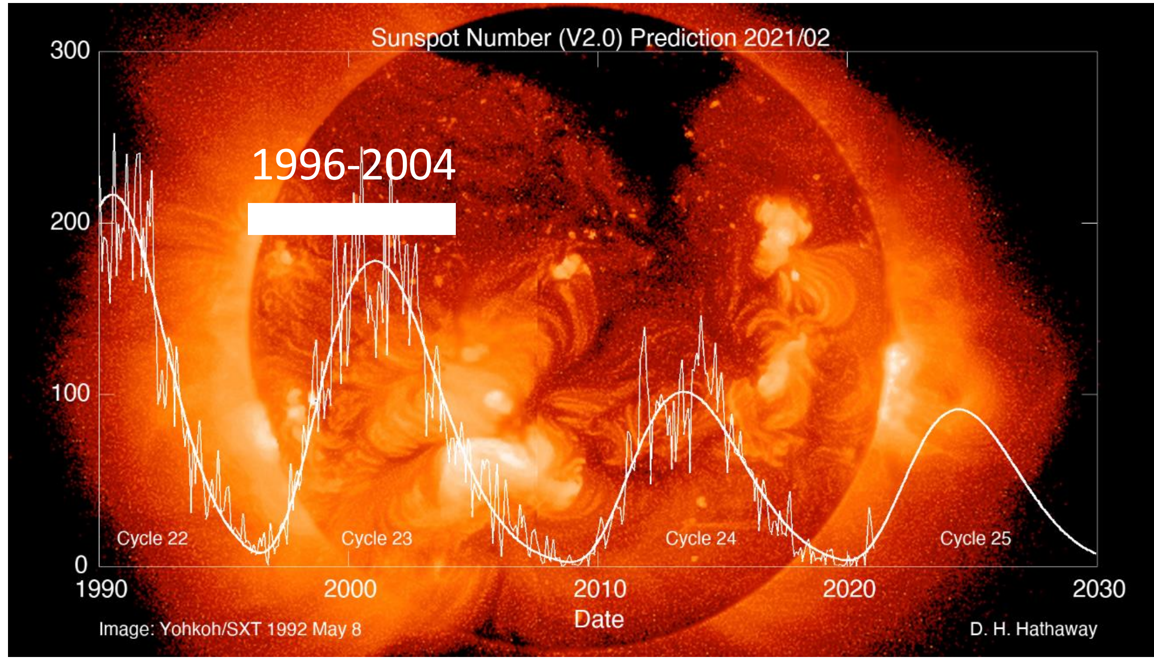
Full Disk MDI
Line-of-Sight Magnetogram





Our Forecasting Database of MDI Magnetograms





MDI Sample
1996-2004

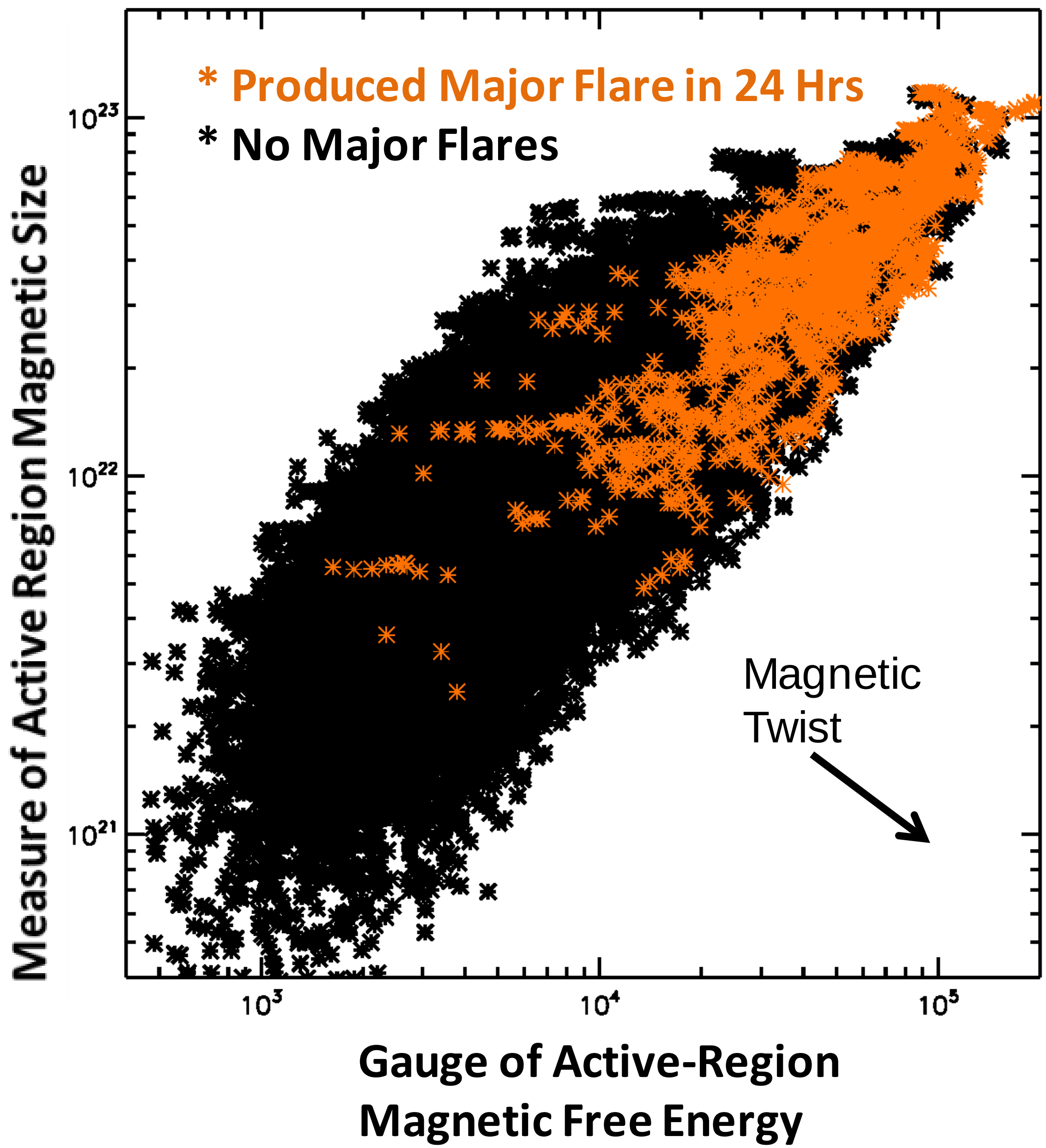
Solar Cycle Plot from David Hathaway, NASA

40,000 Active-Region Magnetograms
1,300 Active Regions

Type of Active Region that produces Major flares/CMEs

A Productive Active Region has:

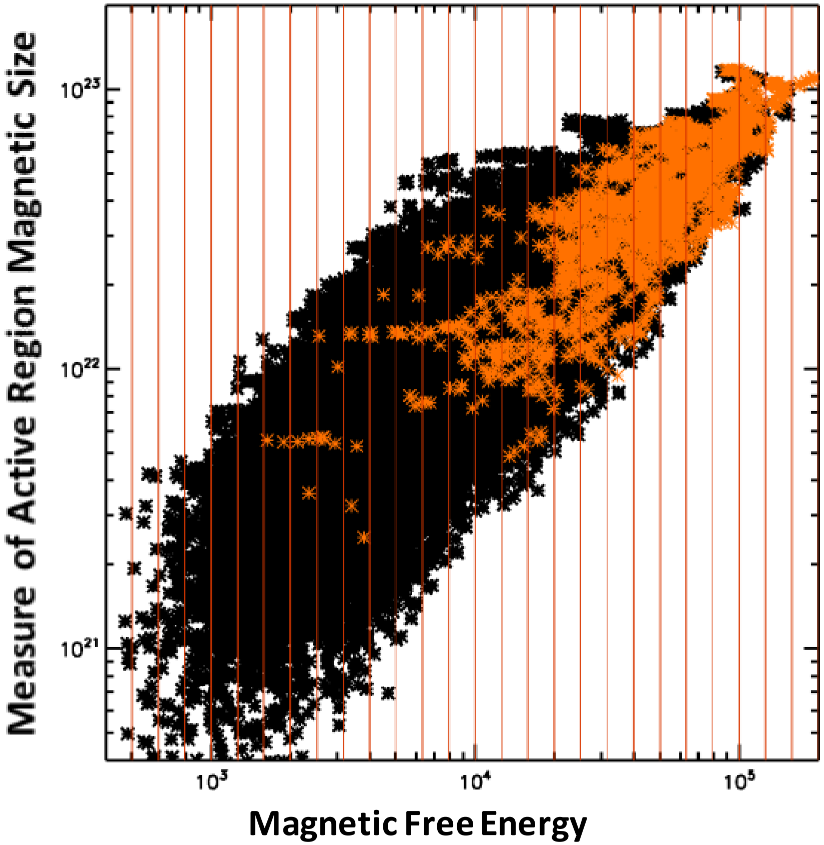
- Large amount of free energy
- Large magnetic size
- Large magnetic twist
- Plot is for major flares.
- Similar tendencies for production of CMEs.

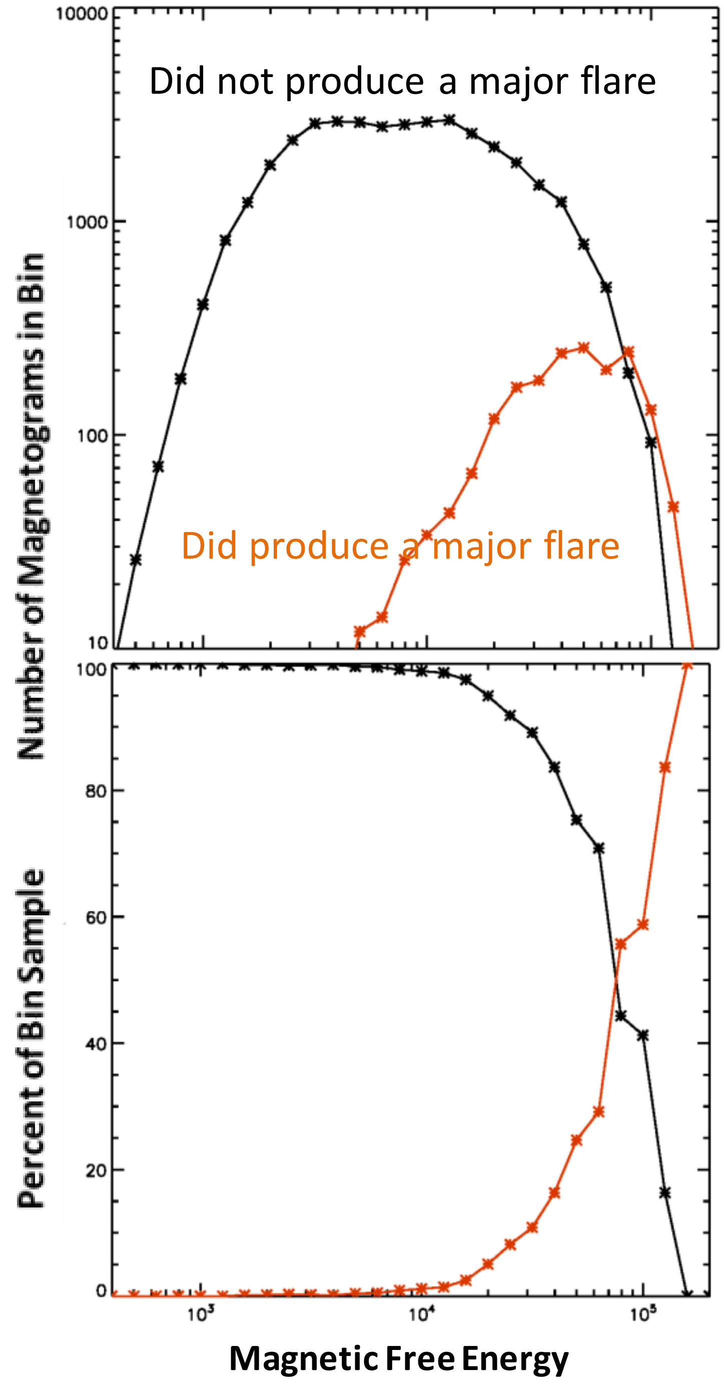


Empirical Forecasting

(Example for Major Flares)

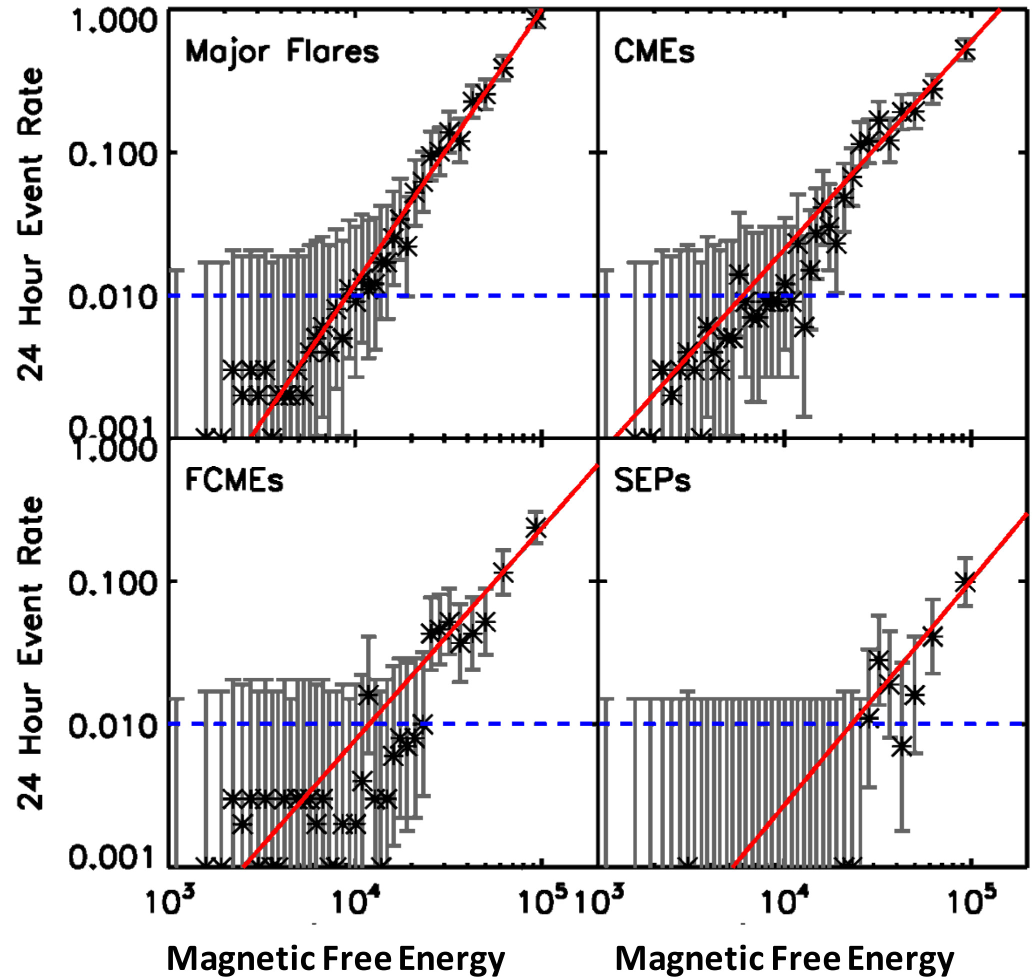
By dividing the sample into bins of free energy, and determining the number of active-region magnetograms of active regions that did not produce a major flare in the next 24 hours and the number that did, we have the basis of a forecasting tool.



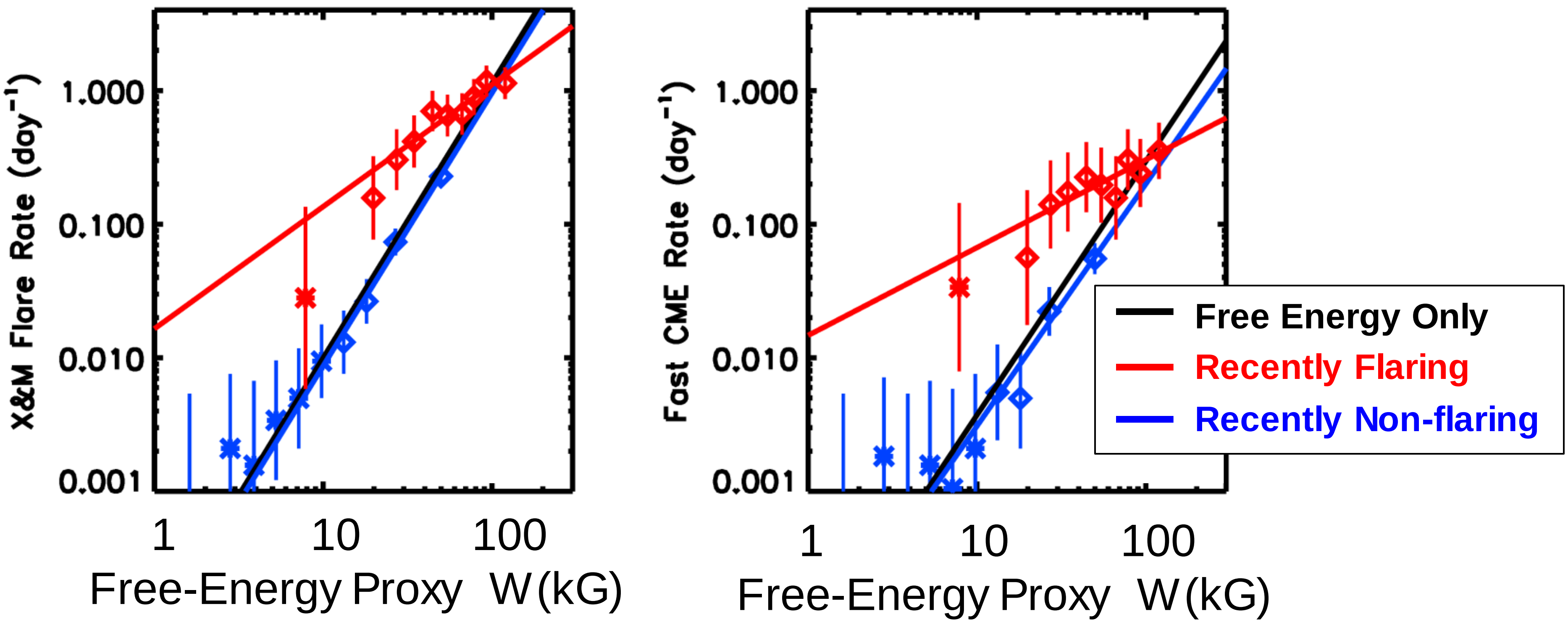


Space Weather Forecasting Curves

- Have found a power-law relationship between our gauge of the free magnetic energy and event rate.
- This occurs for major flares, CMEs, Fast CMEs, and Solar Energetic Particle Events.
- By using this relationship, we can forecast the chance that an event, will be produced by a newly observed active region for which the free energy gauge is measured. (This method is like that for forecasting the chance of rain tomorrow.)



Forecast Curves



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

Outline

- The Threat of Space Weather
- The Science
- **Research to Operations (R2O)**

Present NOAA/AFWA Forecasting Technique

McIntosh Technique

1. Classify AR into one of ~60 McIntosh category.
2. Use empirical database to predict event rate.
3. Modify forecast by human forecaster.

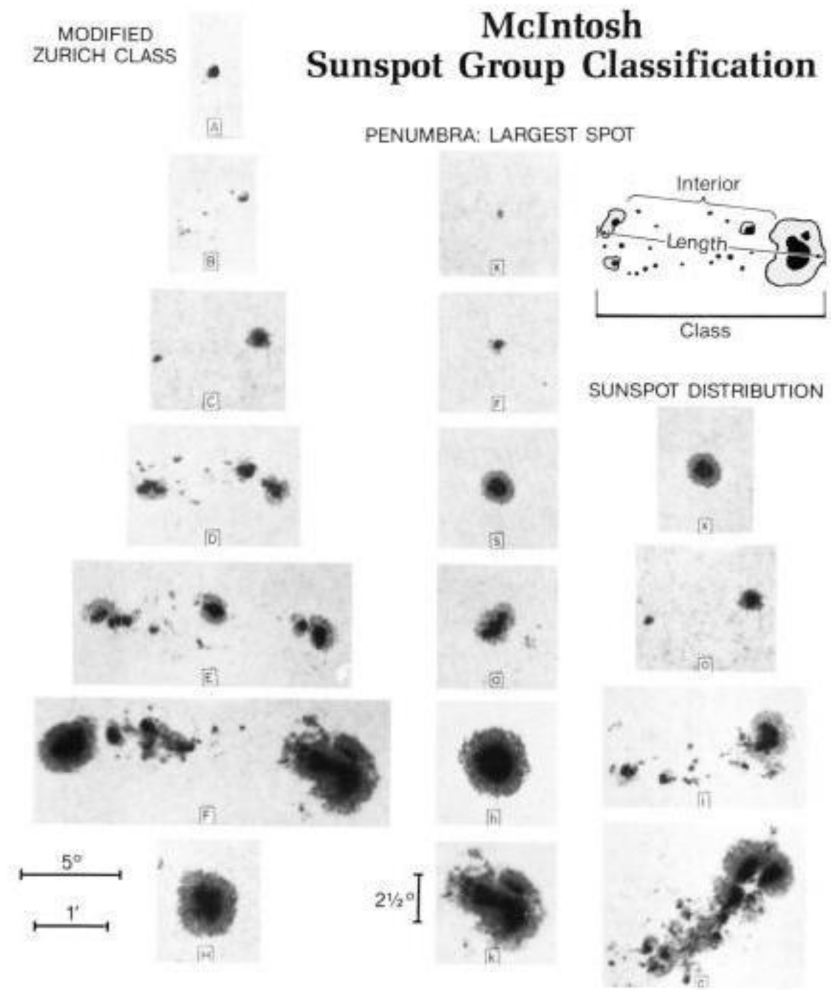


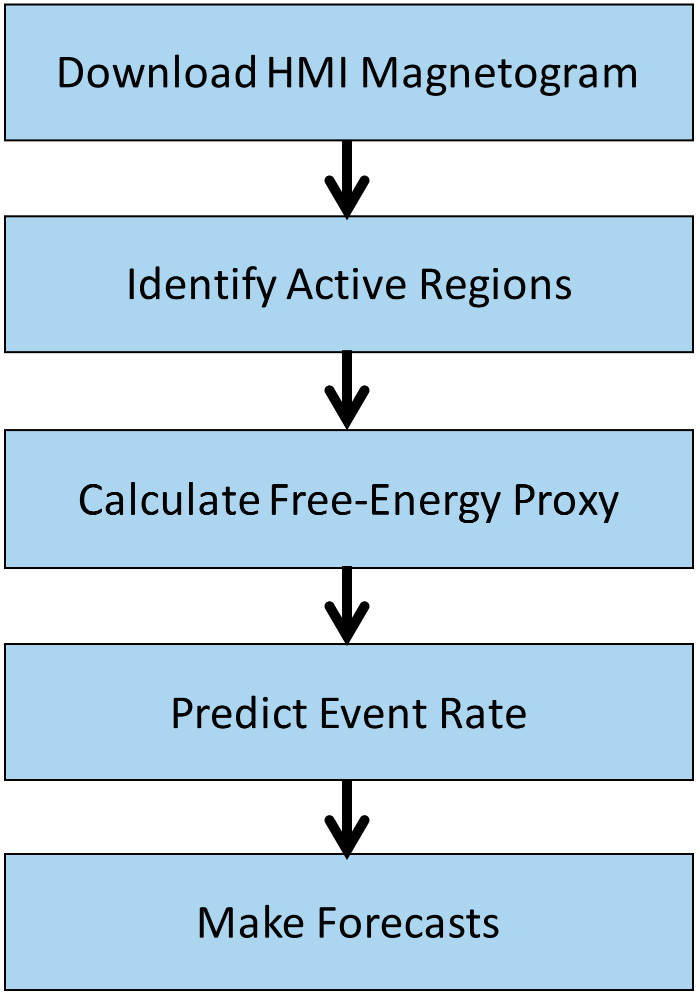
Fig. 1. The 3-component McIntosh classification, with examples of each category.

NOAA/SWPC Pat McIntosh

Methods Presented at April 2013 Meeting

- **Recent Flare Activity** (Wheatland 2004, 2005)
- Magnetic complexity (Abramenko 2005; Georgoulis 2012; McAtteer et al. 2005)
- **Helioseismology signatures** (Komm et al. 2005; Reinard et al. 2010),
- **Photospheric flows** (Welsch et al 2009)
- **Total magnetic flux** (Barnes & Leka 2008; Leka & Barnes 2007),
- **Free-energy proxies** (Falconer 2001; Falconer et al. 2002, 2003, 2006, 2008, 2011; Leka & Barnes 2003a,b; Cui et al. 2006; Jing et al. 2006; Georgoulis & Rust 2007; Schrijver 2007; Mason & Hoeksema 2010)
- **Combination of a free-energy proxy and previous flare history** (Falconer et al. 2012).

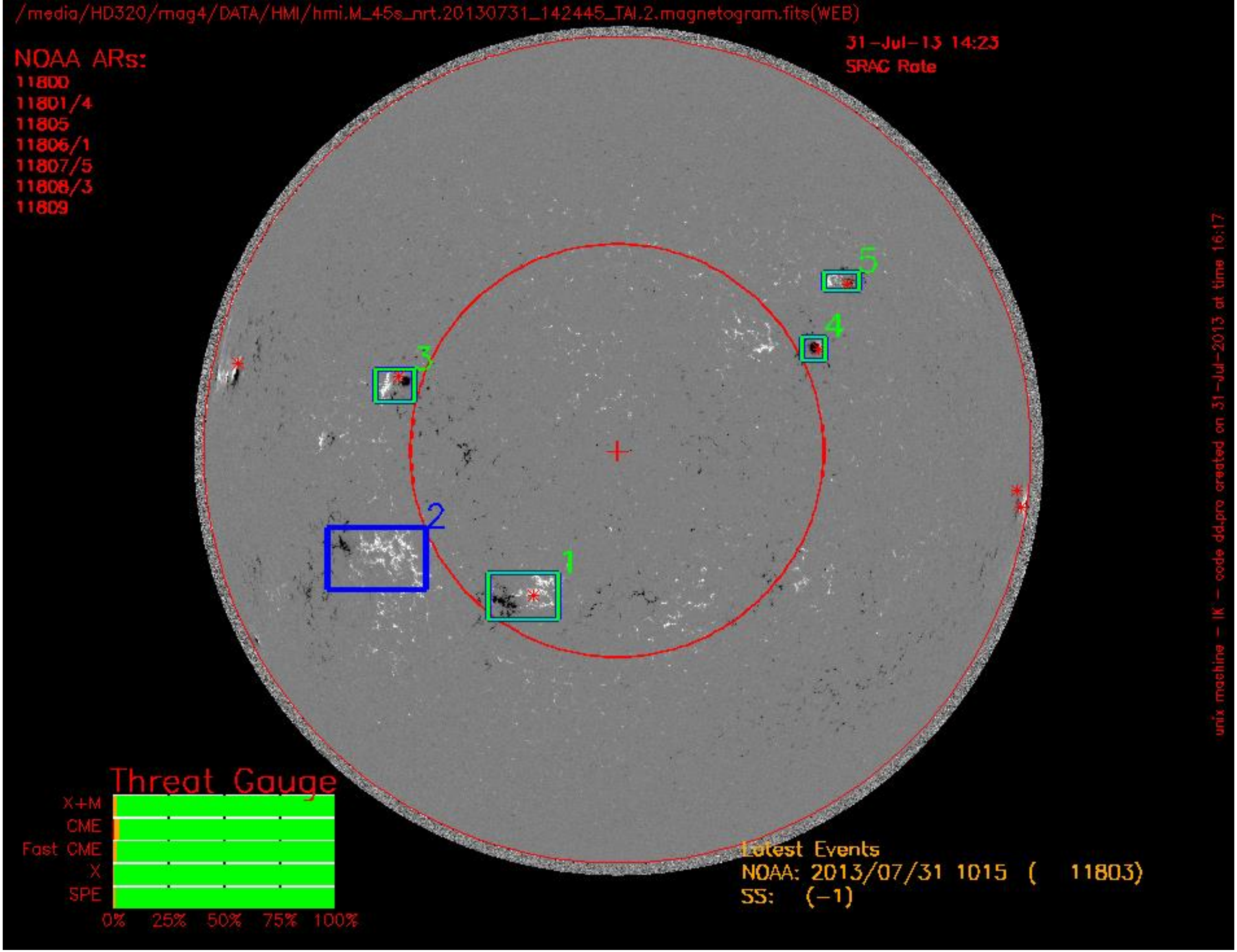
MAG4 Automated Processes



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

Forecasts are probability

Not Time and Magnitude!



/media/HD320/mag4/DATA/HMI/hmi.M_45s_nrt.20130731_142445_TAI.2.magnetogram.fits(WEB)
NOAA ARs:
11800
11801/4
11805
11806/1
11807/5
11808/3
11809
31-Jul-13 14:23
SRAC Rate
unix machine - IK - code dd.pro created on 31-Jul-2013 at time 16:17
1
2
3
4
5
Threat Gauge
X+M
CME
Fast CME
X
SPE
0%
25%
50%
75%
100%
Latest Events
NOAA: 2013/07/31 1015 (11803)
SS: (-1)

Comparison of Safe and Not Safe Days

June 26, 2013

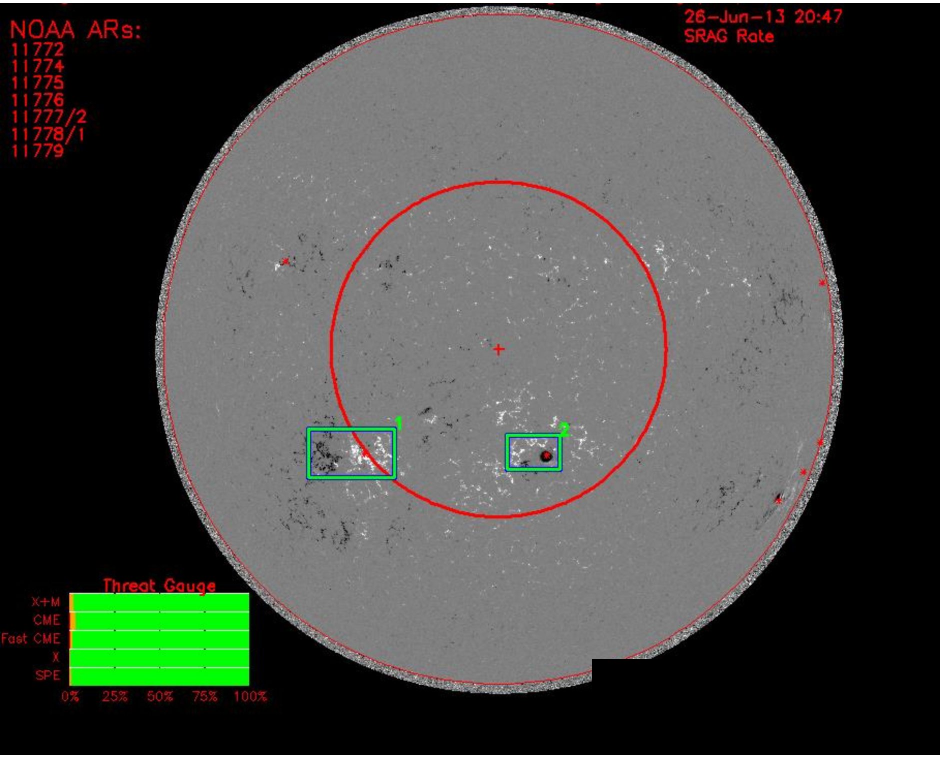
C1, C1.5 flares

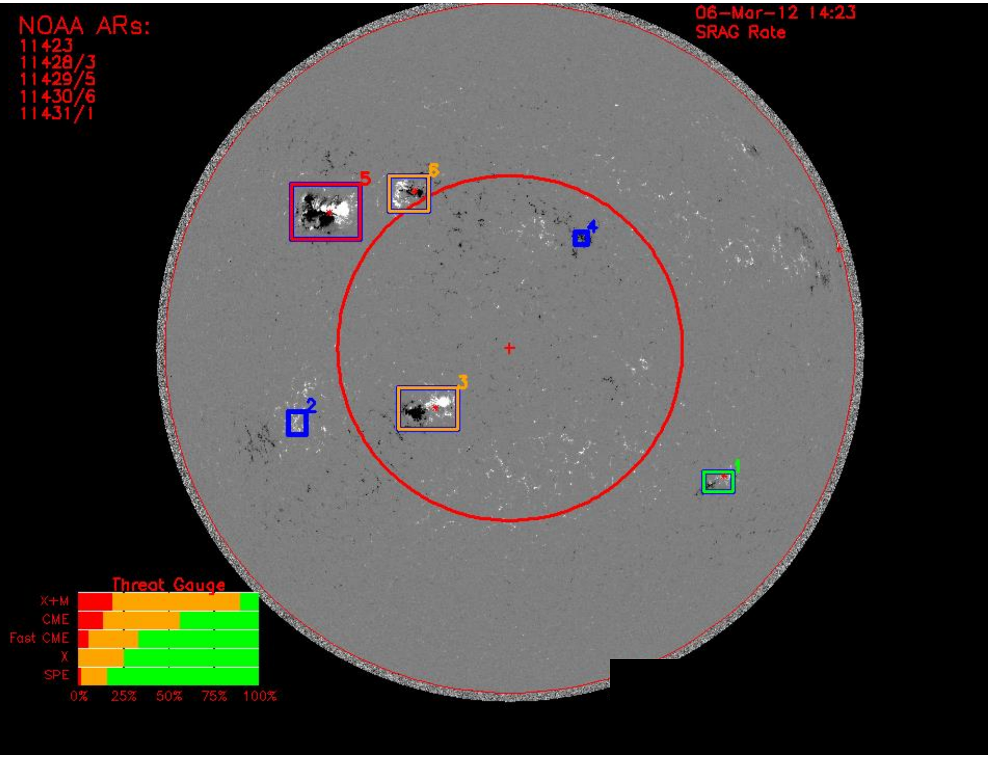
March 7, 2012

X5.4, X1.3, C1.6

CME 2684, 1825 km/sec,

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

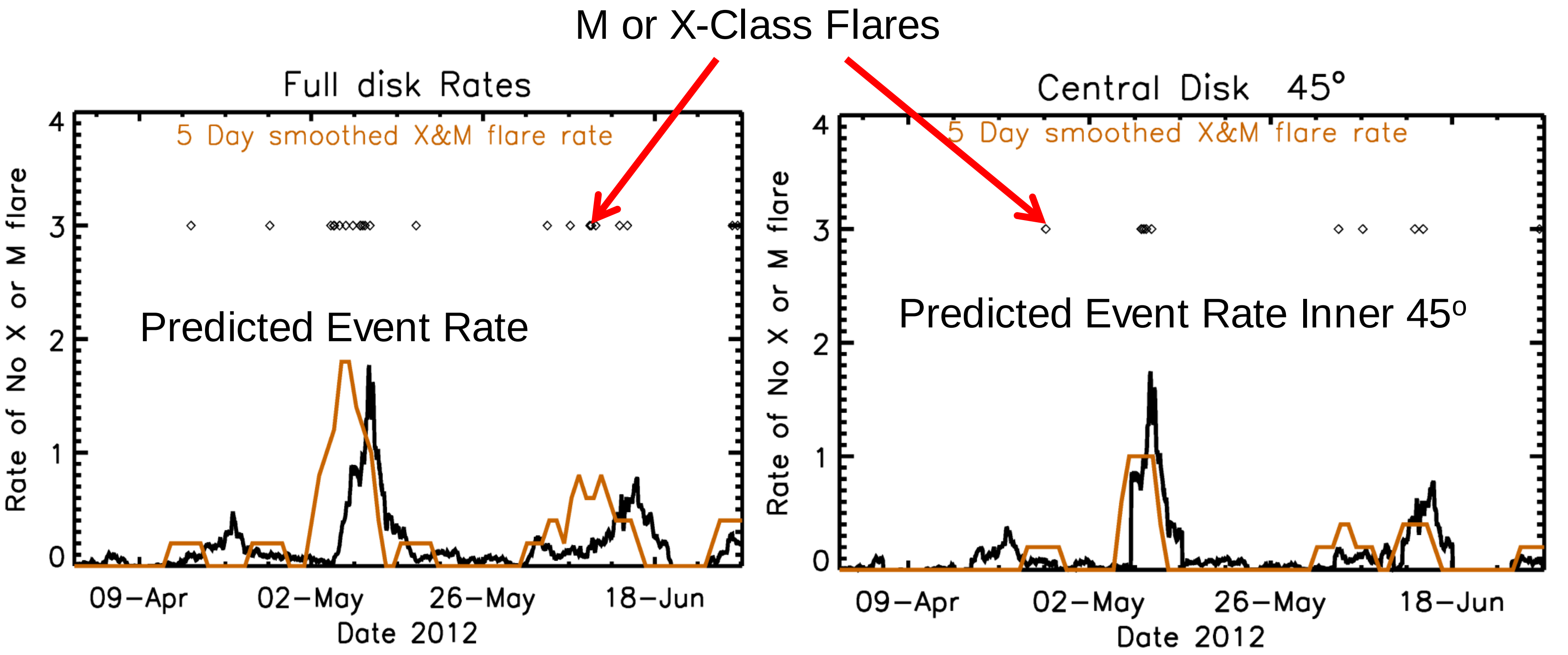




How Well Does MAG4

Situational Awareness

- During periods when flare-productive active regions cross the disk, the predicted rate and actual rate both increase, providing situational awareness
- The results are best when flares and predicted rates are limited to inner 45 degree circle (Right)



Forecast Skill Score

Definitions

	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))

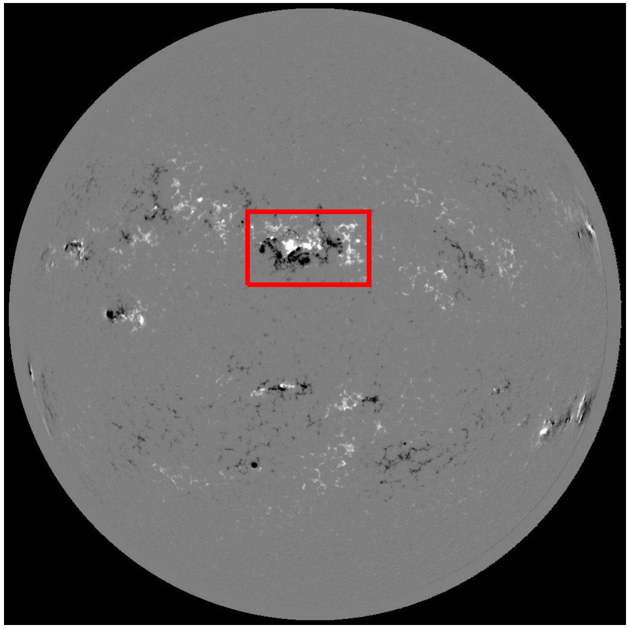
How Well Does MAG4

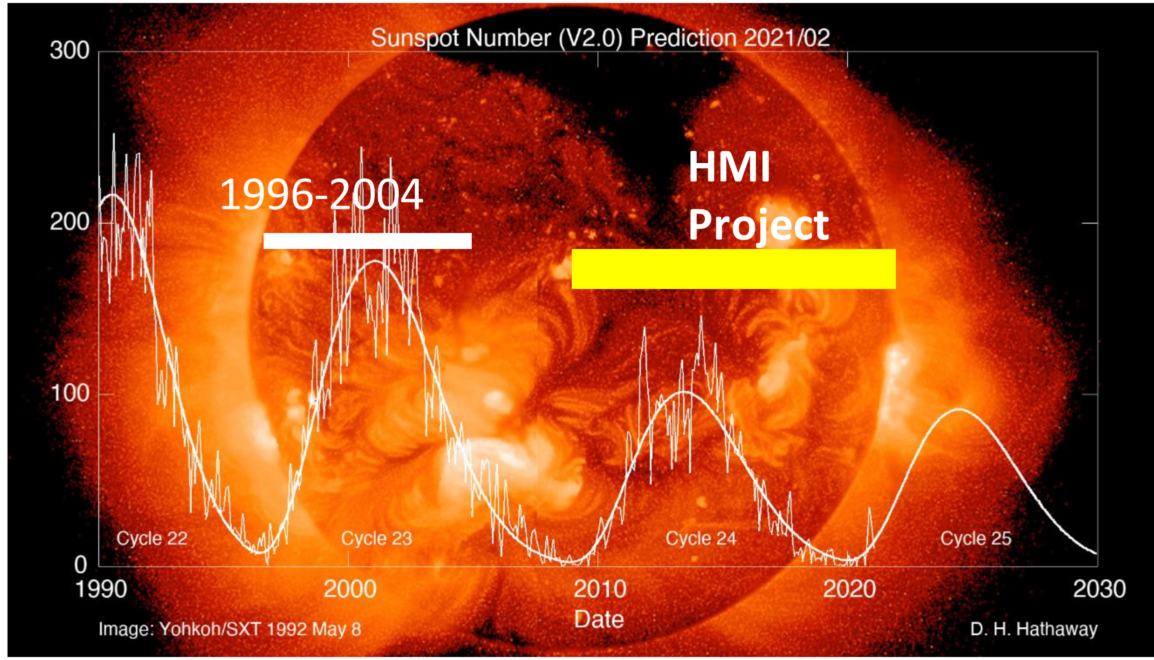
Skill Metrics Significance of Upgrade

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	19114	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)**

Our Forecasting Database of HMI Magnetograms





MDI Sample
1996-2004

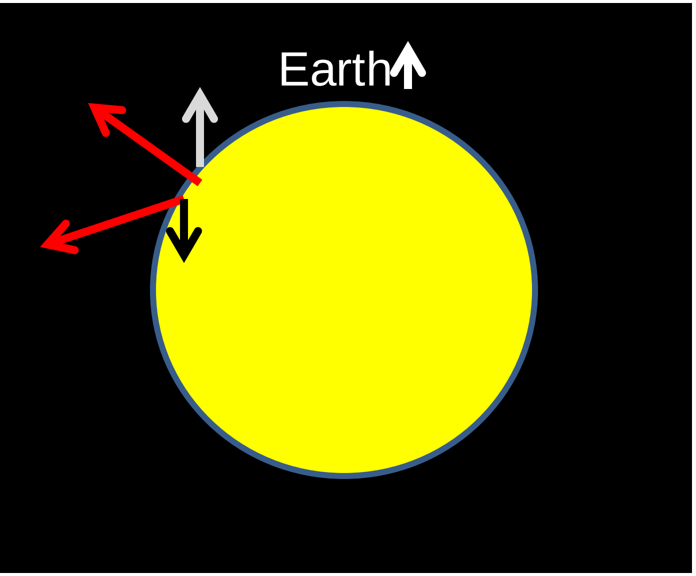
Solar Cycle Plot from David Hathaway, NASA

40,000 Active-Region Magnetograms
1,300 Active Regions

HMI 2010-Present

MAG4 Improvements: Vector Magnetograms

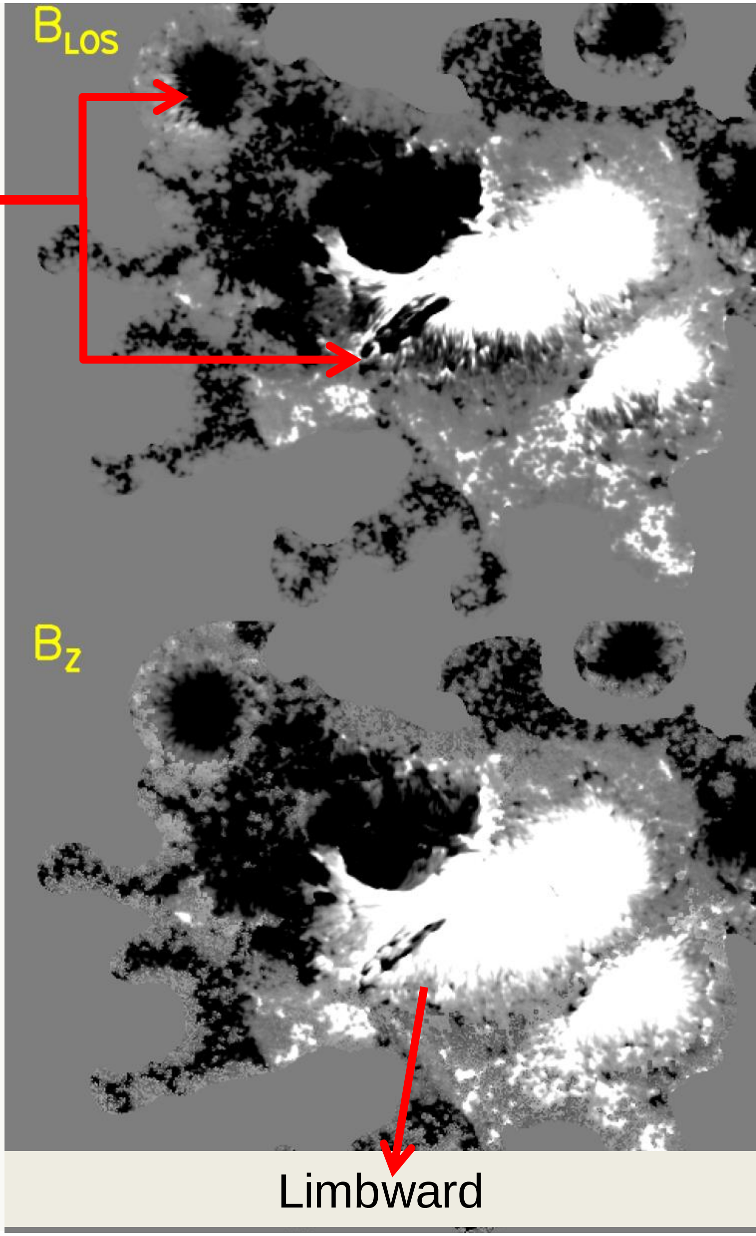
- Both vectors shown in red have positive B_z (magnetic field out of the sun), but have opposite sign B_{LOS} and thus a false (unphysical) neutral line in the line-of-sight (LOS) field.



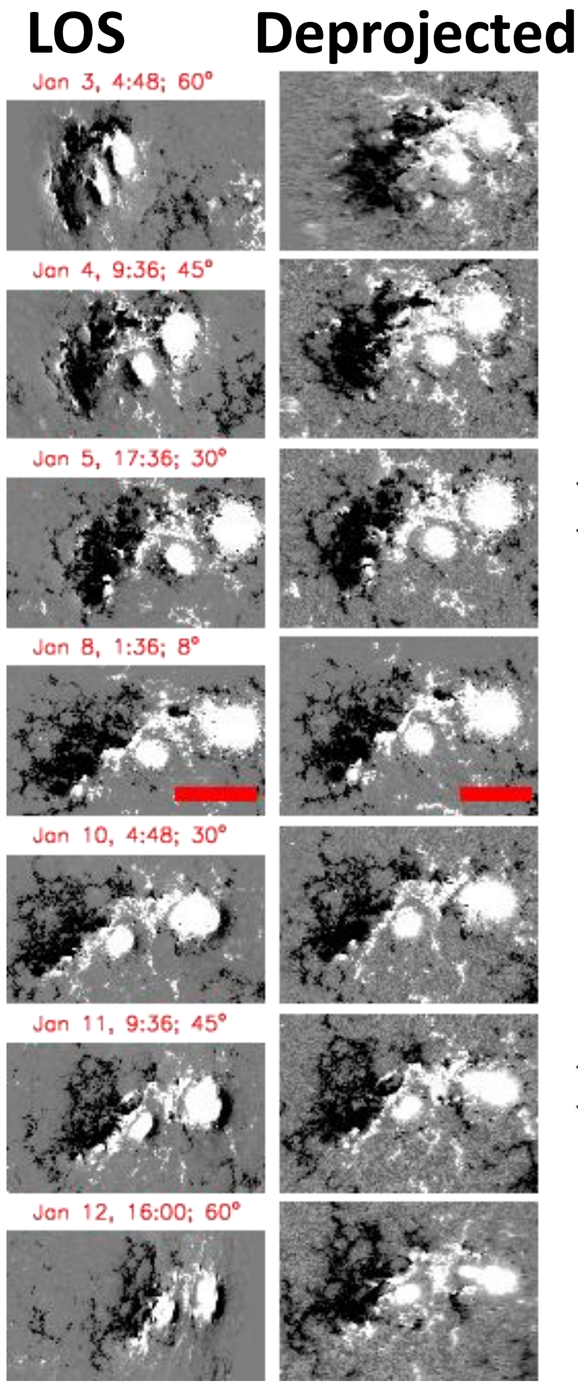
Actual Examples

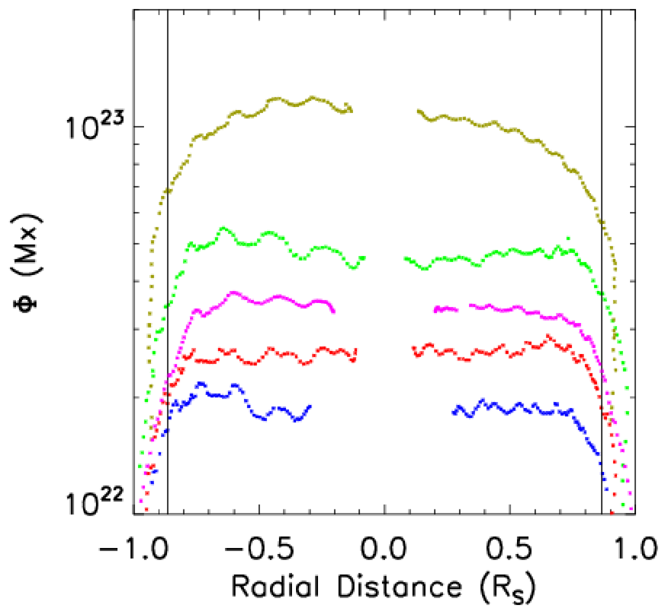
False Neutral Lines occur on limbward sides of sunspots.

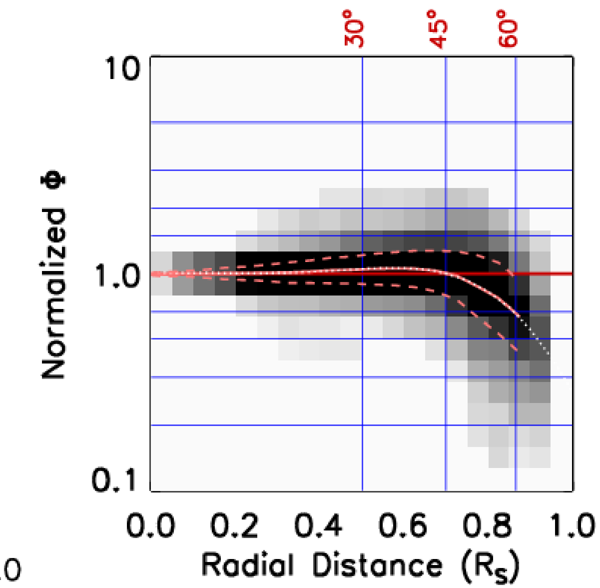
Problem fixed by converting from B_{LOS} and $B_{Transverse}$ to B_Z and $B_{Horizontal}$

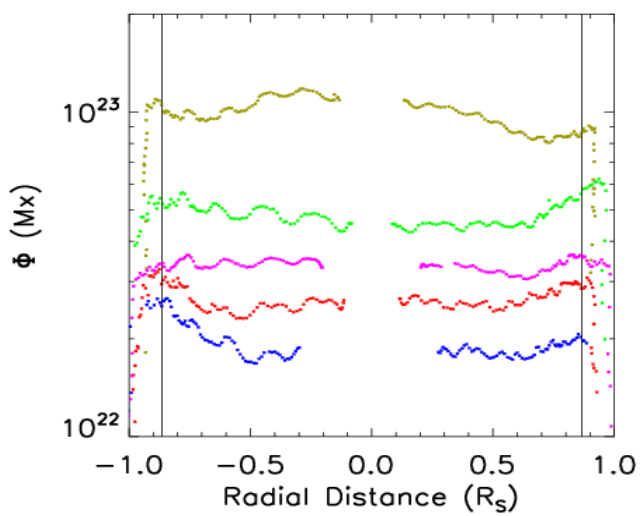


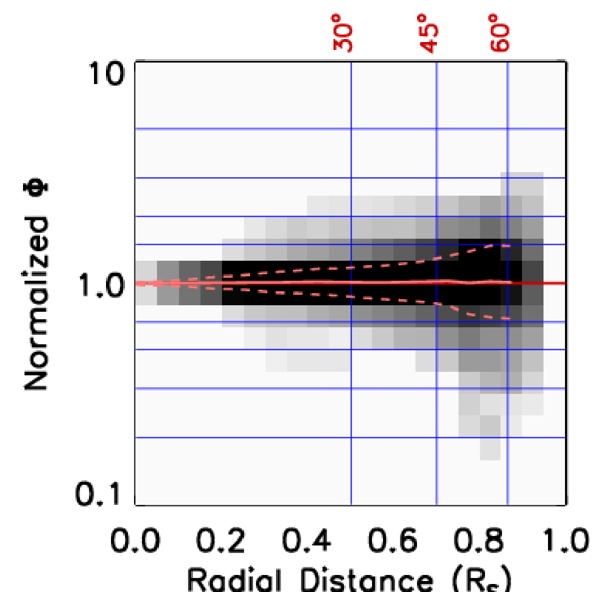
Quantifying and Removing Projection Errors (Falconer et al 2016)











Conclusions

- Space Weather is significant threat, and growing worse
- Forecasting Space Weather is difficult, just like forecasting Earth Weather
- Forecasting though can be done, and can be improved
- There is the need for several NRT observations to improve forecasting, and create reliable databases for further improvement to forecasting

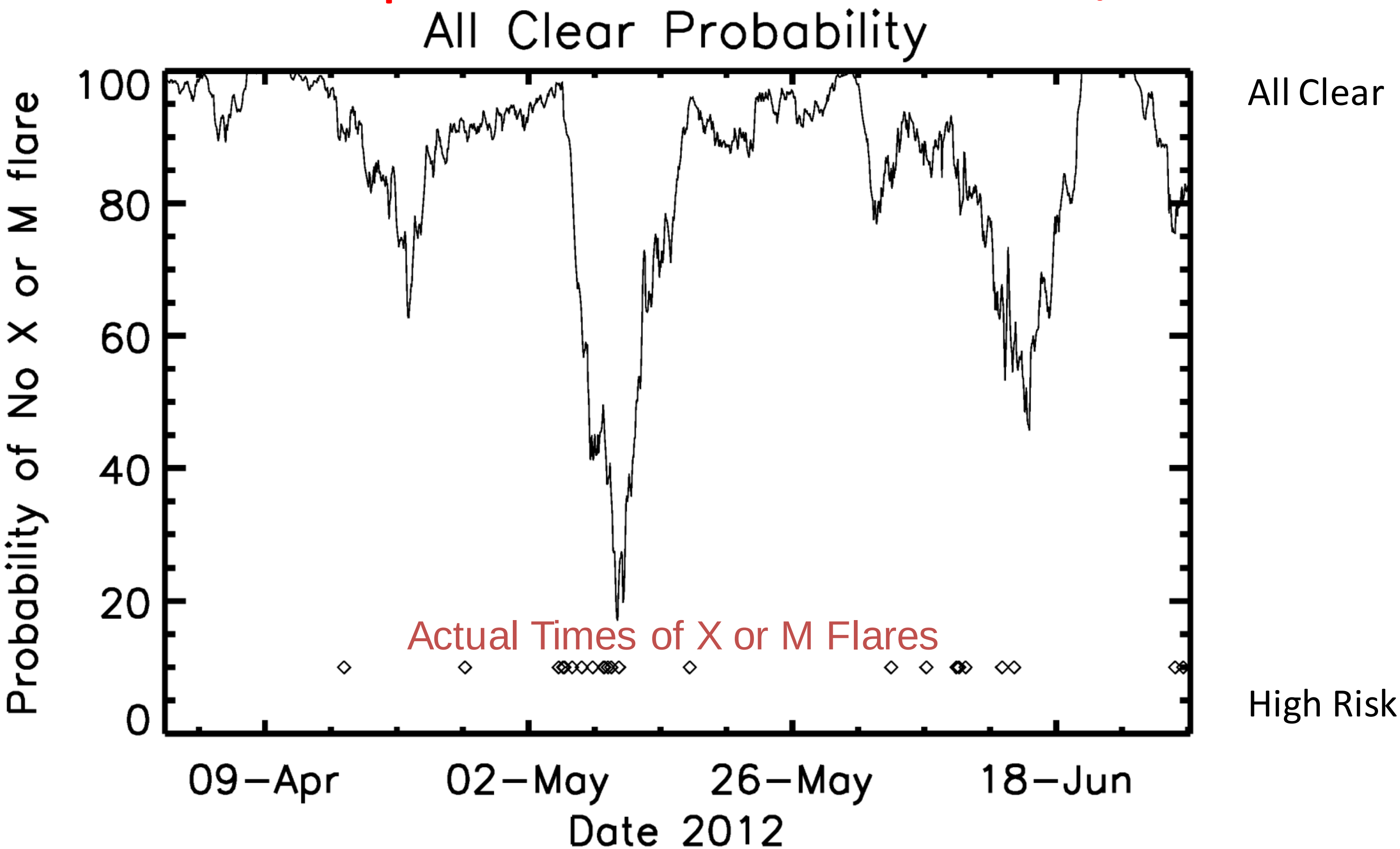
MAG4 Research-to-Operations **Timeline**

- *2011* MAG4 installed at JSC Space Radiation Analysis Group (SRAG) as a NRT (Near-Real-Time) forecasting tool, 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
- *2016* MSFC Software of the Year Award, Honorable Mention for NASA's

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

Dangerous Time Periods Exist

Actual operational data from JSC/SRAG



Magnetic Fields and Solar Eruptions - Theory