How to anticipate flares, and super-flares?

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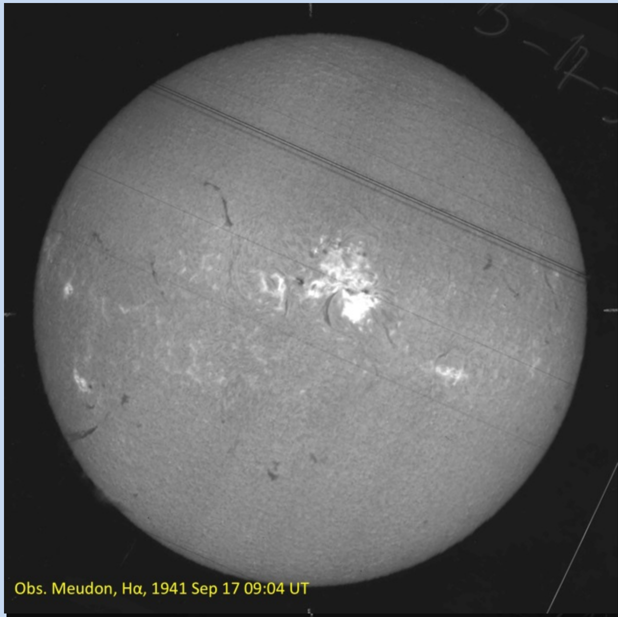
FLARECAST

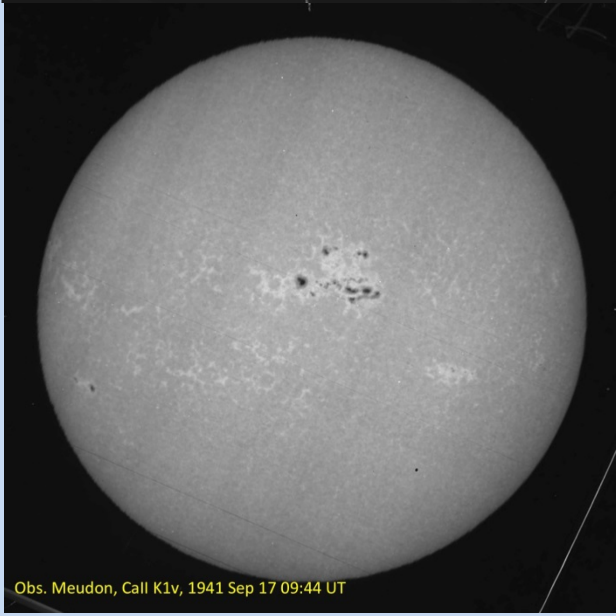
Outline

EM emissions from flares are the first signatures of space-weather relevant disturbances

- What are the associated phenomena: flare/CME relationship?; flares and SEPs?
- What are the terrestrial impacts of flares?
- What are the drivers?
- How to predict flares?
- Can we predict flares together with associated phenomena?

How to define super- flares and extreme events?? How to anticipate them?





A large sunspot observed at Meudon observatory on 17 September 1941

Solar Flares

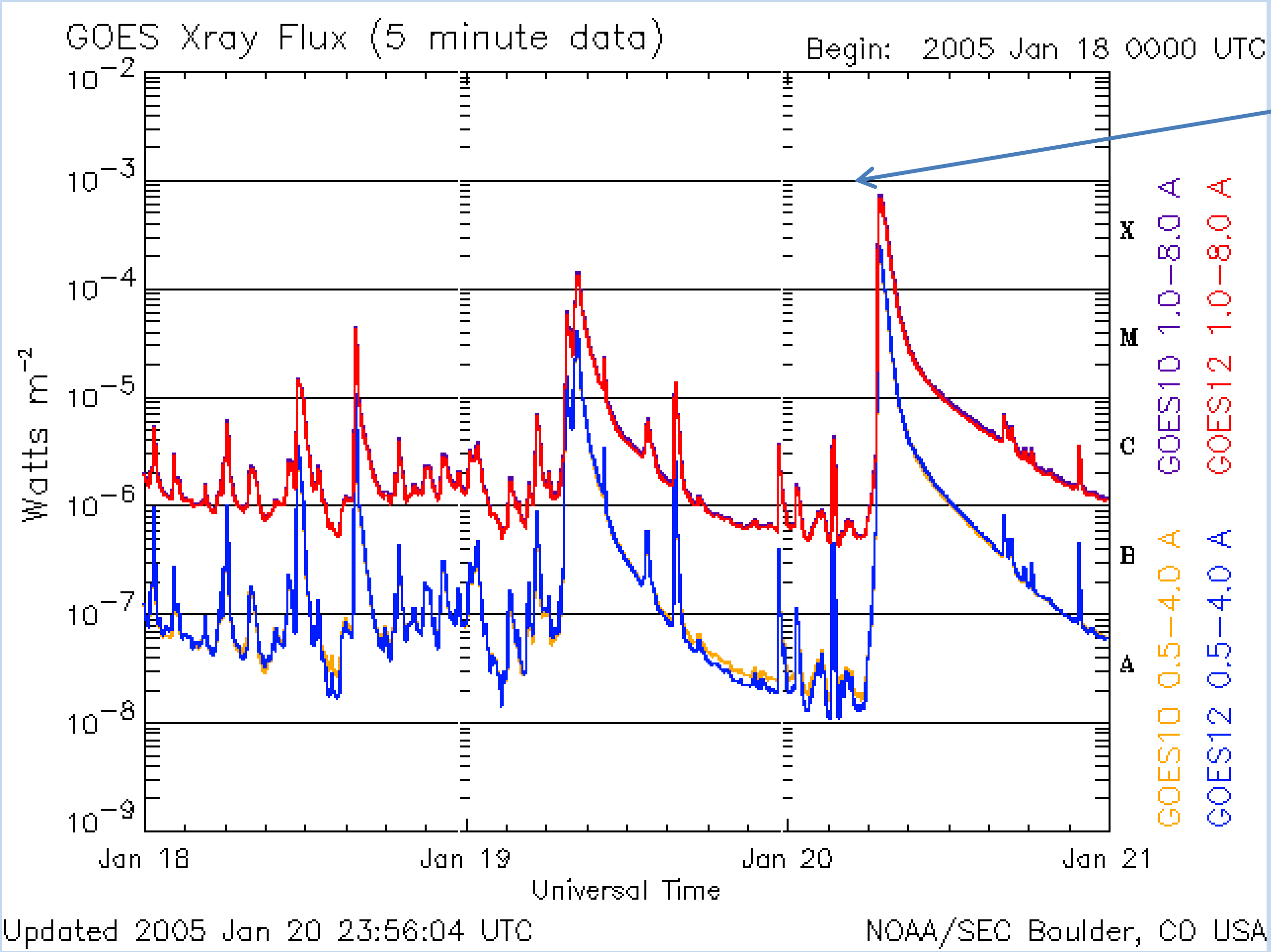
Usually observed in H α
Observations from the Meudon spectroheliograph
28 October 2003

Local and sudden brightening in an active region
Linked to complex magnetic fields
(presence of electric currents in the active region)

Energy :10^{32} ergs, in~1000 s: (typical value)

Longitudinal magnetic field observed
By SOHO/MDI
28 October 2003

X-ray observations of solar flares: GOES observations

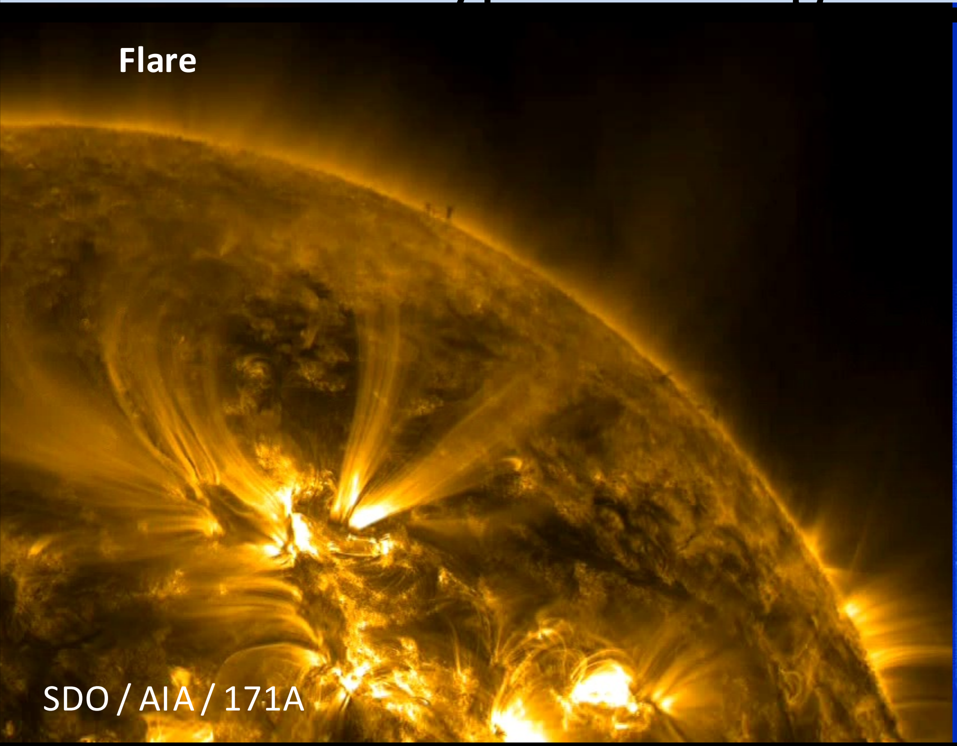


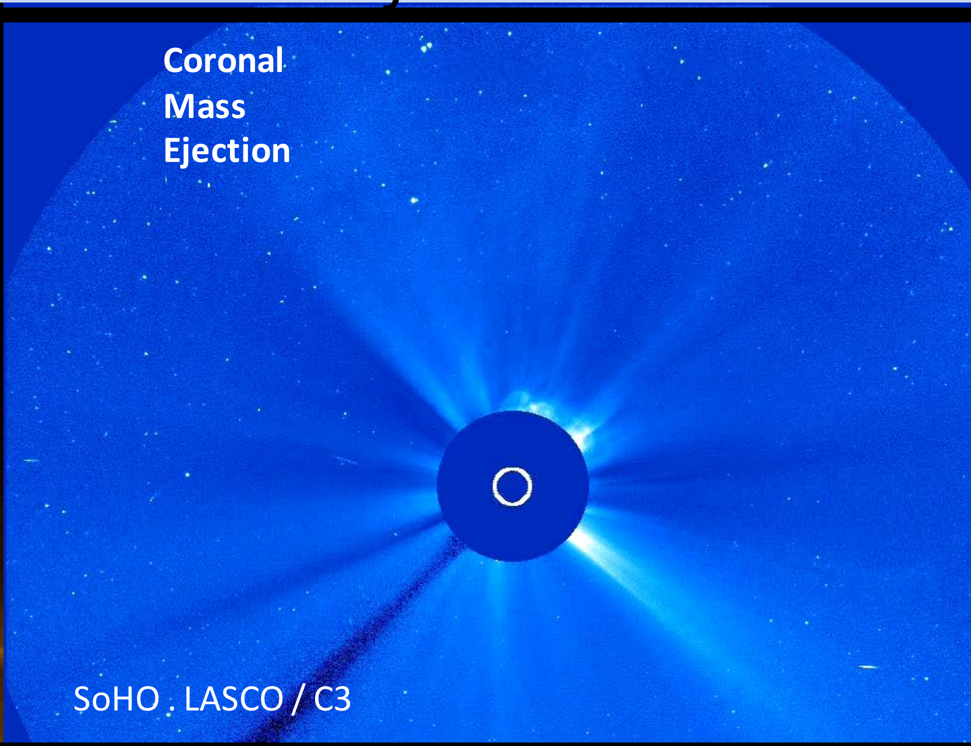
X9 Goes class flare
20 January 2005

Total X-ray Flux
In 2 wavelengths bands:
X-ray flare characterized by T and Em
Em emission measure $N^2 V$ (cm^{-3})
T around 10^{7} K
Thermal bremsstrahlung

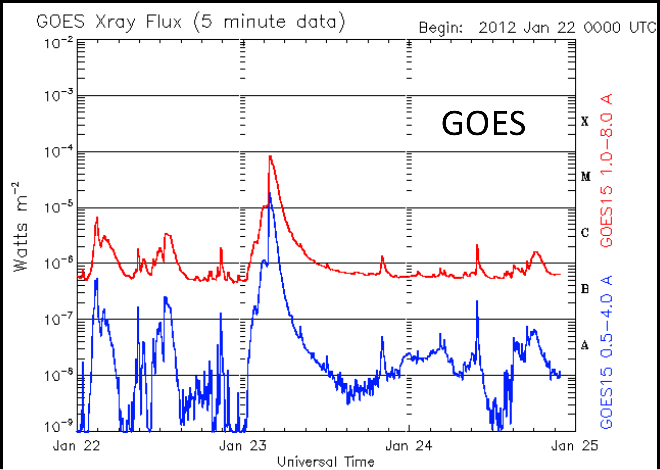
Continuous survey (start 1975)

A typical strong solar flare – *M9 flare*

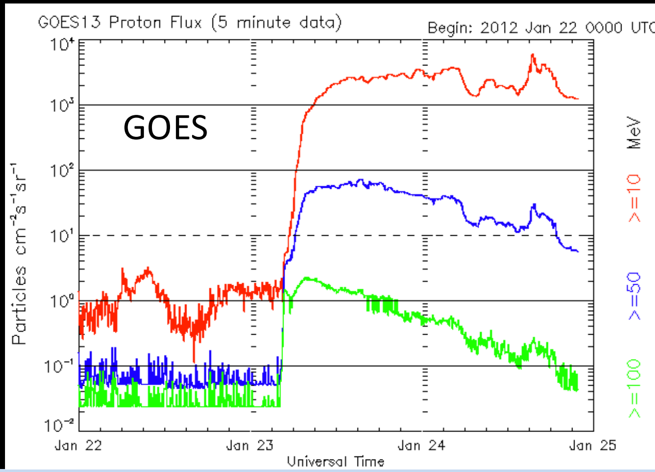




Soft X-rays

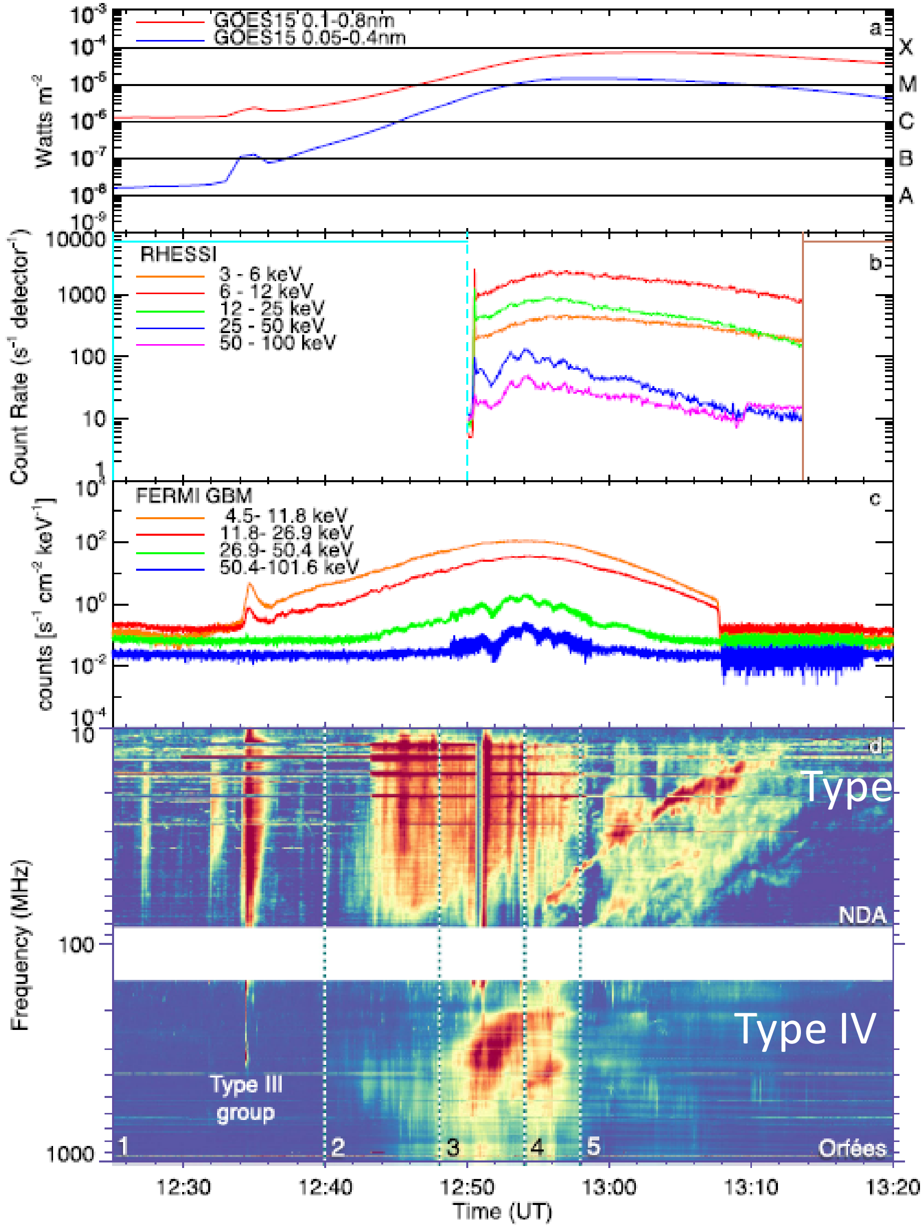


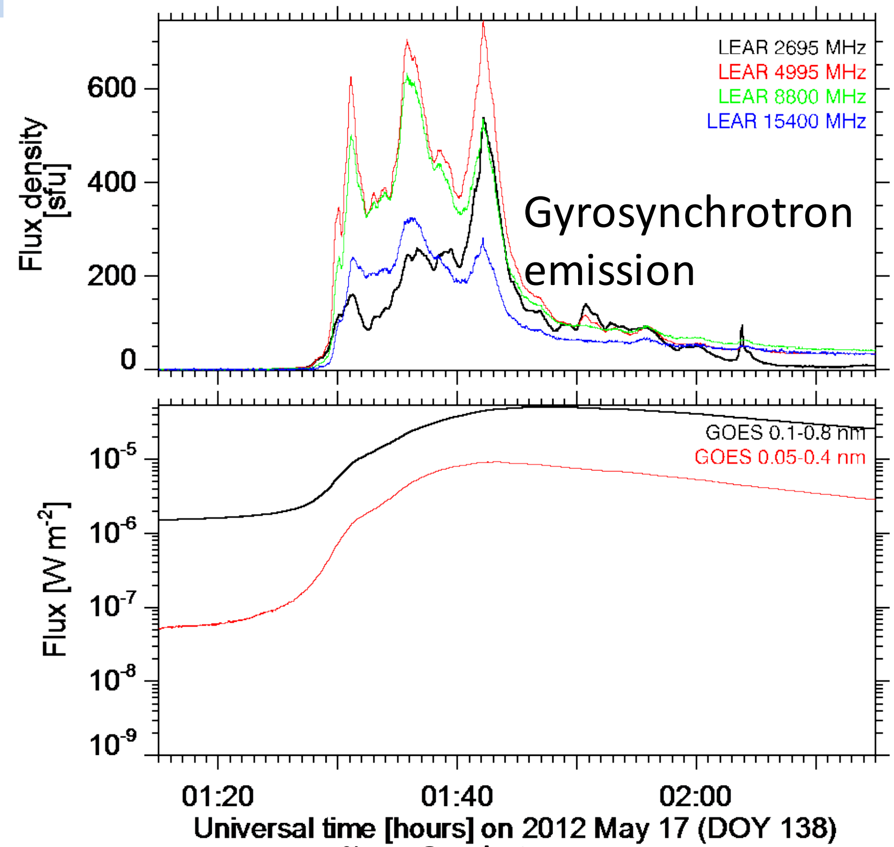
Solar Energetic Particles



A typical solar flare associated with a fast CME (> 2000 km/s) and the fast arrival of protons at Earth(courtesy of G. Aulanier)

Solar flares are associated with strong X-ray and radio emissions:





Zucca, Nuñez & Klein , JSWSC 2017

Observations of GOES M5 ; M8 class flares

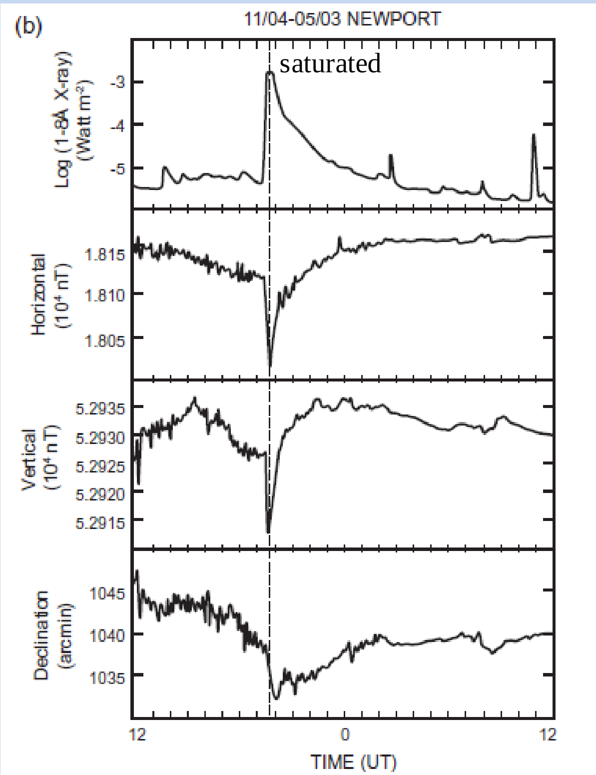
Strong Radio Observations in the whole Frequency band

Also associated with fast CMEs and SEPs

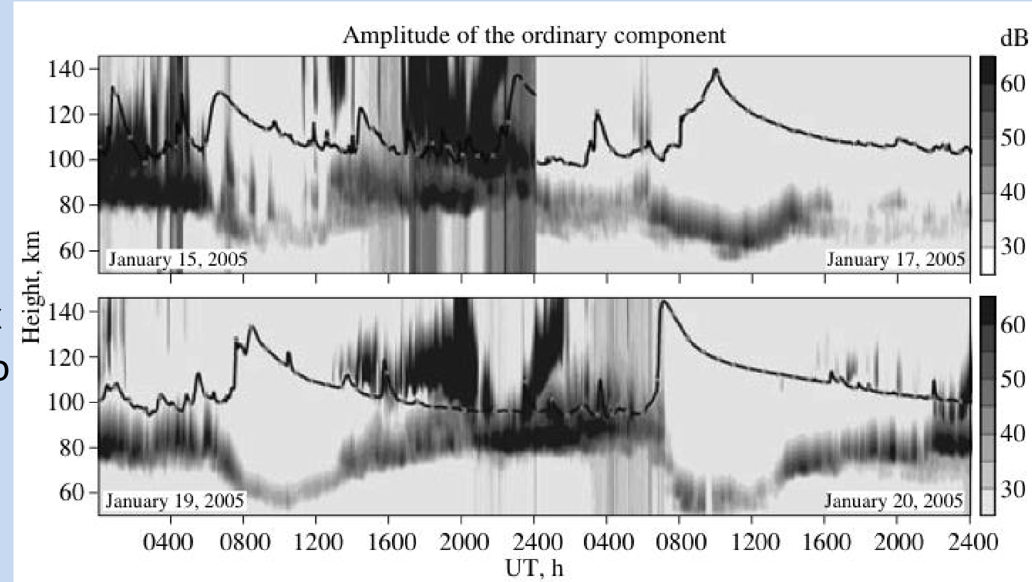
Carley, Vilmer & Gallagher, ApJ 2016

A few direct (and almost immediate) effects of solar flares: disturbances for radio communications

X 35 +/- 10

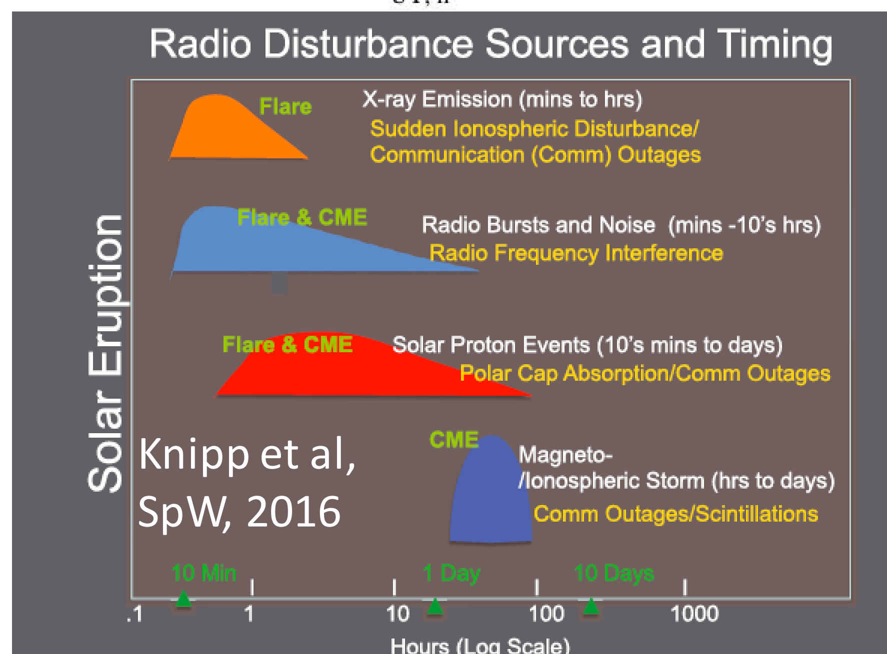


Amplitude of radio echo in the polar D ionosphere and X-ray flux (Tereshchenko et al., 2006)



04 November 2003 flare

Flares are associated with magnetic « crochet » (SFE) and sudden ionospheric disturbance (Cliver & Dietrich, JSWSC, 2013) and changes the conditions in the ionosphere radio waves propagation.



Knipp et al, SpW, 2016

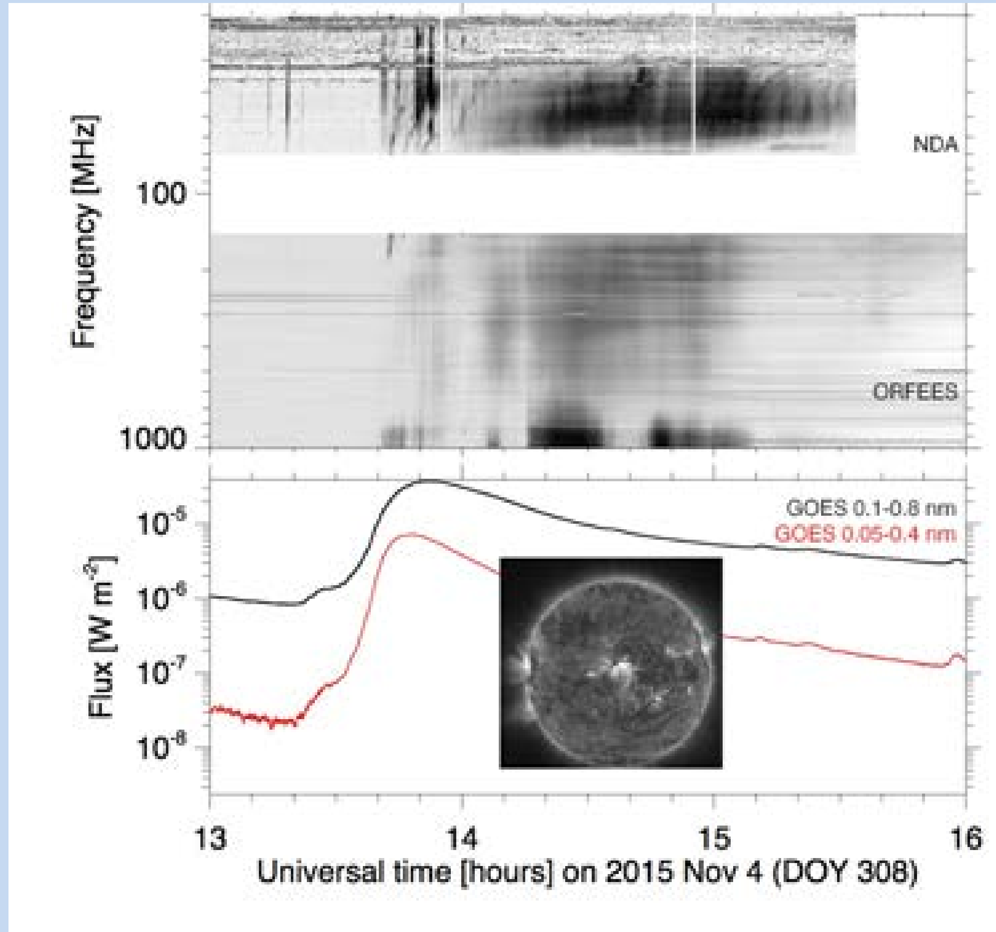
A Solar Flare affects airports in Sweden!: The radio event?

SCIENCES

EN BREF

Une éruption solaire perturbe les grands aéroports en Suède
Une éruption solaire a brièvement mis hors d'usage mercredi les radars des grands aéroports du sud de la Suède et entraîné d'importants retards, a annoncé la direction de l'aviation civile. Vers 15 h 45, des tempêtes solaires ont perturbé les champs magnétiques terrestres, provoquant un dysfonctionnement des radars utilisés par les aiguilleurs pour réguler le trafic. Les aéroports de Stockholm-Arlanda, Stockholm-Bromma, Malmö et Göteborg ont été touchés pendant environ une heure.

Le Figaro
05/11
2015



Radars work at 1.03 and 1.09 GHz
https://www.obs-nancay.fr/Emission-radio-du-soleil-et-radars-de-controle-aerien-les-observations-solaires.html

Radio data from Nançay (Paris Observatory)

- **10^3 sfu at ~ 1 GHz**
- **(Marque, Klein et al., in prep)**

How and Why to Anticipate/ Forecast Solar Flares?

A few questions and preliminary comments
(see also invited talk by K.D. Leka on Friday)

Why predict flares: Flares have direct terrestrial and almost immediate effects

If possible to *predict flares, predict associated phenomena?*

Such as CMEs? SEPs?

BUT Predicting flares is very challenging:

Flares (especially major flares) are intrinsically stochastic processes : they follow a time-dependent Poisson appearance process

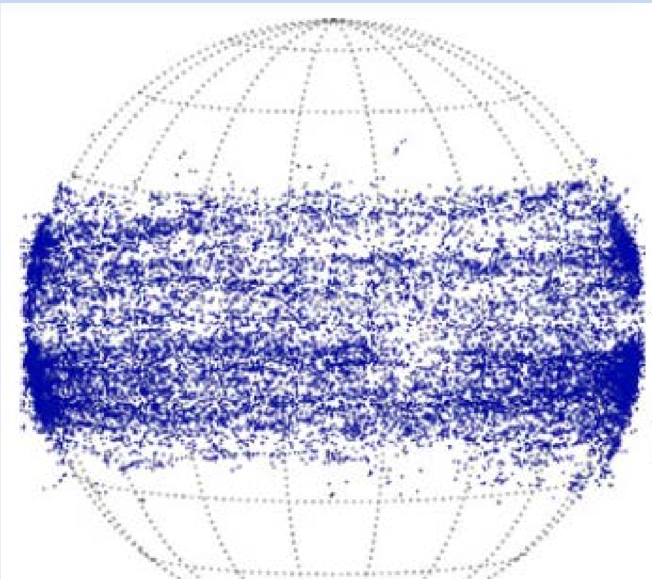
Usually probabilistic forecast

If possible to predict flares can we additionally predict:

when, how big

association with enhanced radio emissions ?

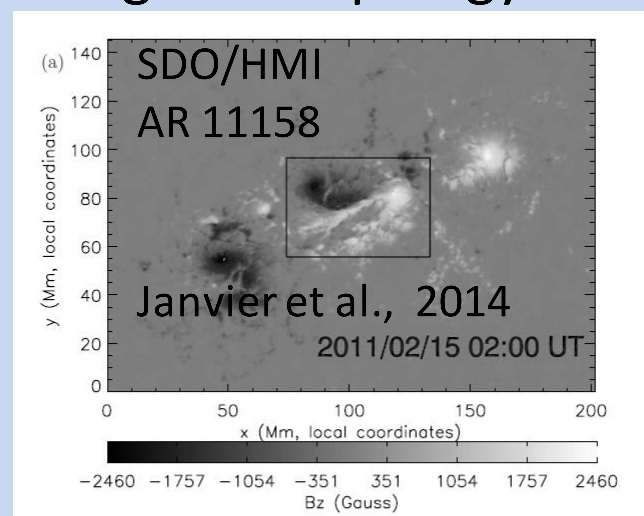
How to anticipate/ predict flares: some observational guidelines

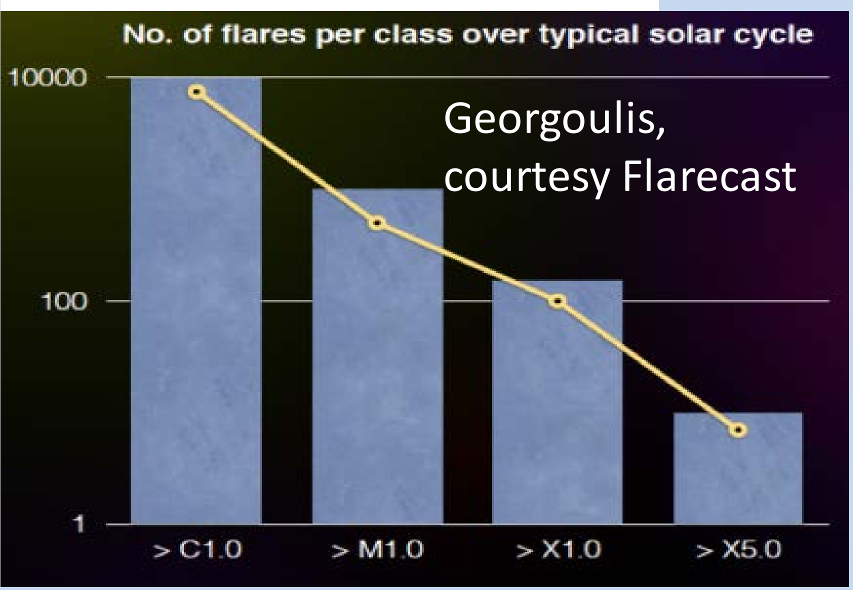


Hannah et al., 2011

Flares (even microflares) occur in ARs (24,097 microflares observed by RHESSI)

Flares occur in ARs with opposite magnetic polarity and complex magnetic topology



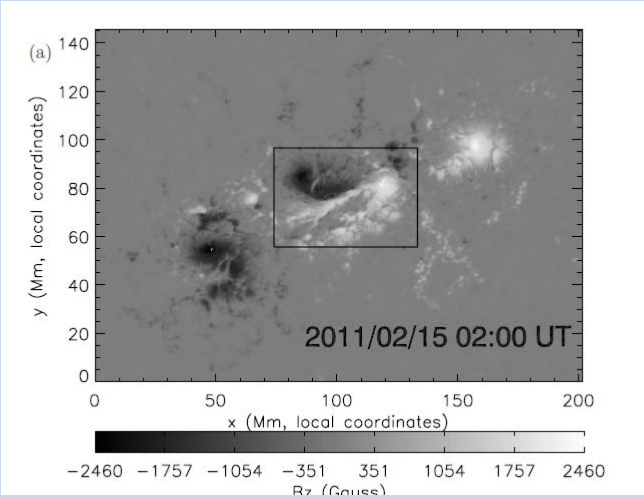


BUT < 2% of solar active regions will produce a X-class flare

<10% of solar active regions will produce M-class flare

How to anticipate/ predict flares: some observational guidelines

Solar flares are believed to result from magnetic reconnection in AR regions in which magnetic energy is stored



A lot of predictive tools based on the classification of AR regions based either on white light or magnetic field classification (Mc Intosh class or magnetic class) and a probabilistic approach based on the occurrence rate of different classes of flares (e.g. GOES class flares) established on previuosly observed AR characteristics and measured flares (see e.g. talks on Friday)

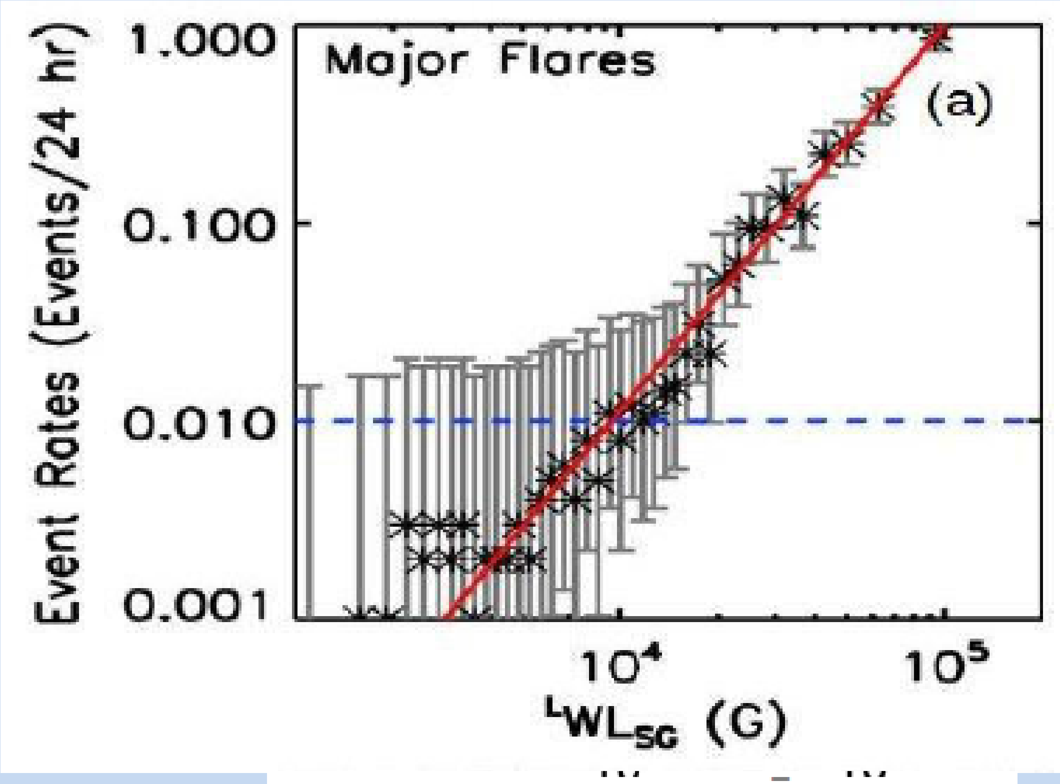
Many AR properties are derived from magnetic field measurements:
Length of the polarity inversion line (PIL)
Integral of magnetic gradient along the PIL (…)

A lot of work has been achieved based on e.g. previous SOHO/MDI measurements and derived properties in ARs
(see e.g. Barnes et al. 2016 for a comparison of the different flare forecasting techniques)

How to anticipate/ predict flares:

Falconer et al. , SpWea 2011

Some examples of flare forecasting of major flares (X and M) using the properties of the magnetic field gradient along the Polarity Inversion Line



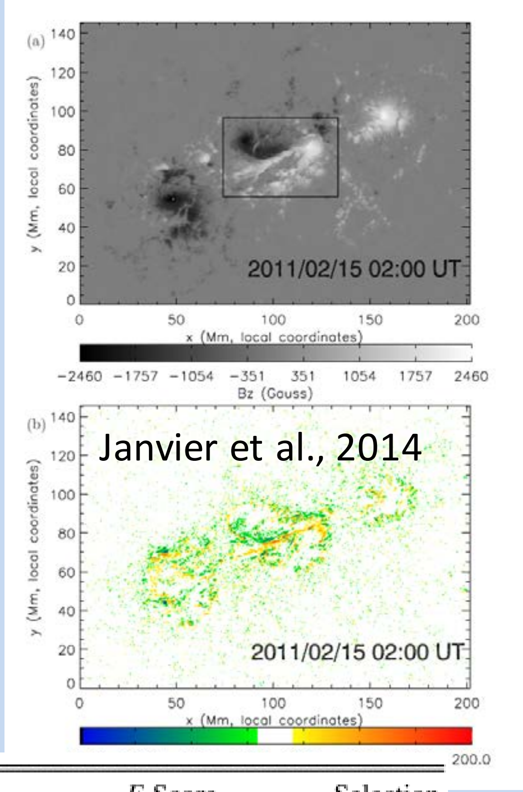
$$\mathrm{WL_{SG}} = \int (\nabla B_z) dl \text{ (G)}$$

How to anticipate/ predict flares: some observational guidelines

Solar flares are believed to result from magnetic reconnection in AR regions in which magnetic energy is stored:
In region with non-potential magnetic fields
In connection with the presence of electric currents…

Nowadays possibility to have measurements of vector magnetic fields and to derive electric currents in ARs with SDO/ HMI
(one of the aim of H2020 FLARECAST project)
(see posters Guerra, Vilmer&Guennou..)

(see also Bobra & Couvidat, ApJ 2015) (below a few parameters derived from AR observations and extracted properties)



Janvier et al., 2014

Keyword	Description	Formula	*F*-Score	Selection
TOTUSJH	Total unsigned current helicity	$H_{c_{\text{total}}} \propto \sum \lvert B_z \cdot J_z \rvert$	3560	Included
TOTBSQ	Total magnitude of Lorentz force	$F \propto \sum B^2$	3051	Included
TOTPOT	Total photospheric magnetic free energy density	$\rho_{\text{tot}} \propto \sum \left(\boldsymbol{B}^{\text{Obs}} - \boldsymbol{B}^{\text{Pot}}\right)^2 dA$	2996	Included
TOTUSJZ	Total unsigned vertical current	$J_{z_{\text{total}}} = \sum \lvert J_z \rvert dA$	2733	Included
ABSNJZH	Absolute value of the net current helicity	$H_{c_{\text{abs}}} \propto \left\lvert \sum B_z \cdot J_z \right\rvert$	2618	Included
SAVNCPP	Sum of the modulus of the net current per polarity	$J_{z_{\text{sum}}} \propto \left\lvert \sum^{B_z^+} J_z dA \right\rvert + \left\lvert \sum^{B_z^-} J_z dA \right\rvert$	2448	Included
USFLUX	Total unsigned flux	$\Phi = \sum \lvert B_z \rvert dA$	2437	Included
AREA_ACR	Area of strong field pixels in the active region	$\text{Area} = \sum \text{Pixels}$	2047	Included
TOTFZ	Sum of *z*-component of Lorentz force	$F_z \propto \sum (B_x^2 + B_y^2 - B_z^2) dA$	1371	Included

How to test different predictors with numerical models?

- Use of several MHD numerical simulations of the formation of stable and unstable magnetic flux ropes (Leake et al., 2013;2014) to evaluate the predictive potential of different parameters derived from magnetic parameters.

- Test of many properties derived from
  magnetic fields, currents
  properties of the PIL
  (Leka & Barnes, 2003)
  (Falconet et al., 2003; 2008)

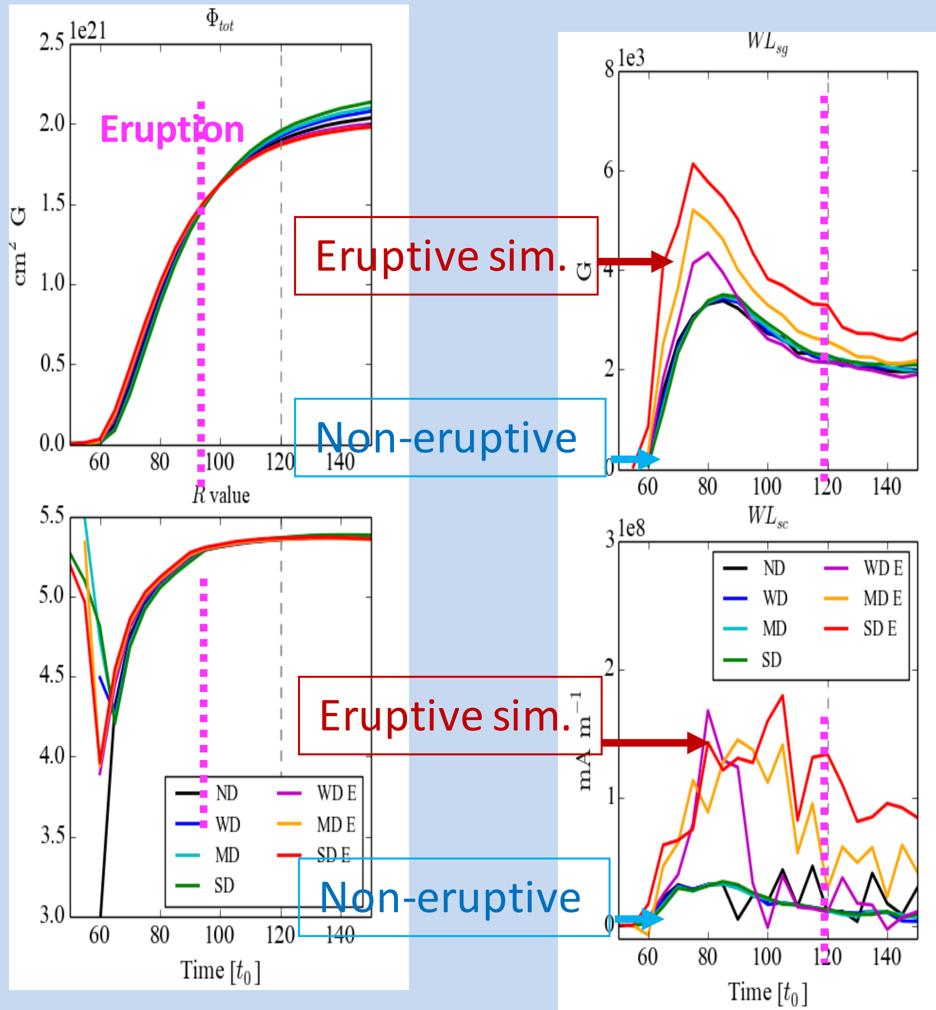
Over the many quantities tested, only the 6 related to the polarity inversion line provide pertinent information in the context of these simulations

(Guennou et al., 2017; see poster)

See also the work on helicity by Pariat et al., 2017

No prediction **Pertinent predictor**

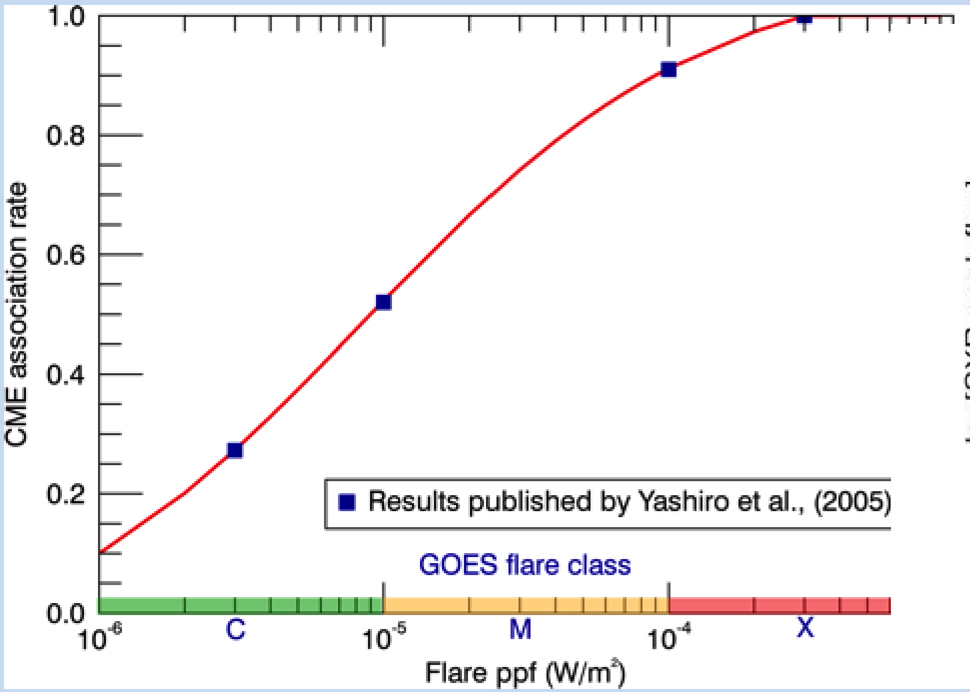
Similar behavior in all the simulations



Different behavior depending on the eruptivity of the simulation

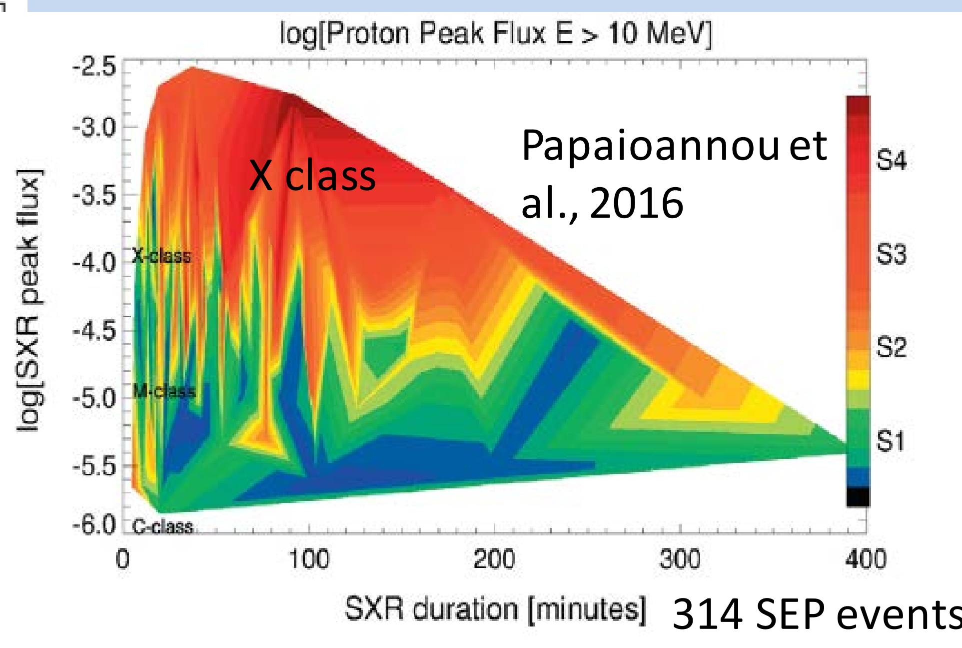
How to anticipate/ predict flares and associated events such as CMEs, SEPs?

If major flares such as M or X class flares can be predicted , then it could be used to predict predict fast CMEs or SEPs



Flares >X3 are usually associated with fast CMEs (Based on the analysis of 1301 X-ray flares (>C3) and associated CMEs observed with SOHO/LASCO

(Georgoulis
FLARECAST First Stakeholders workshop)

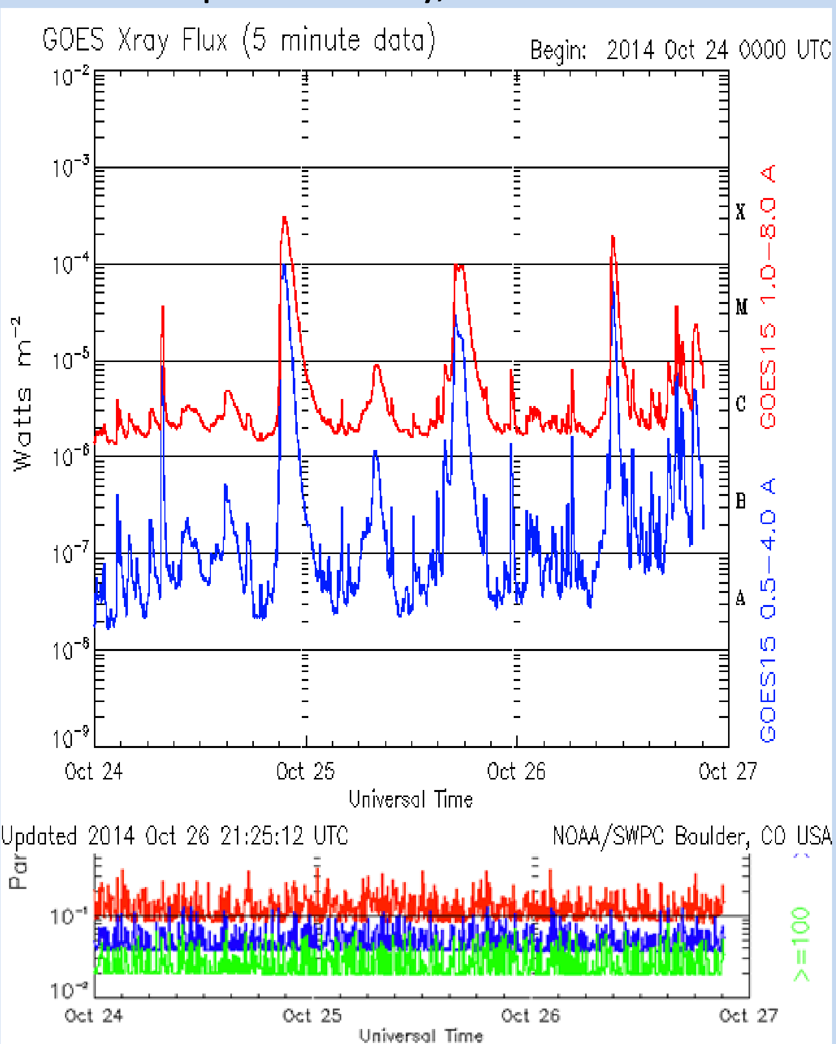


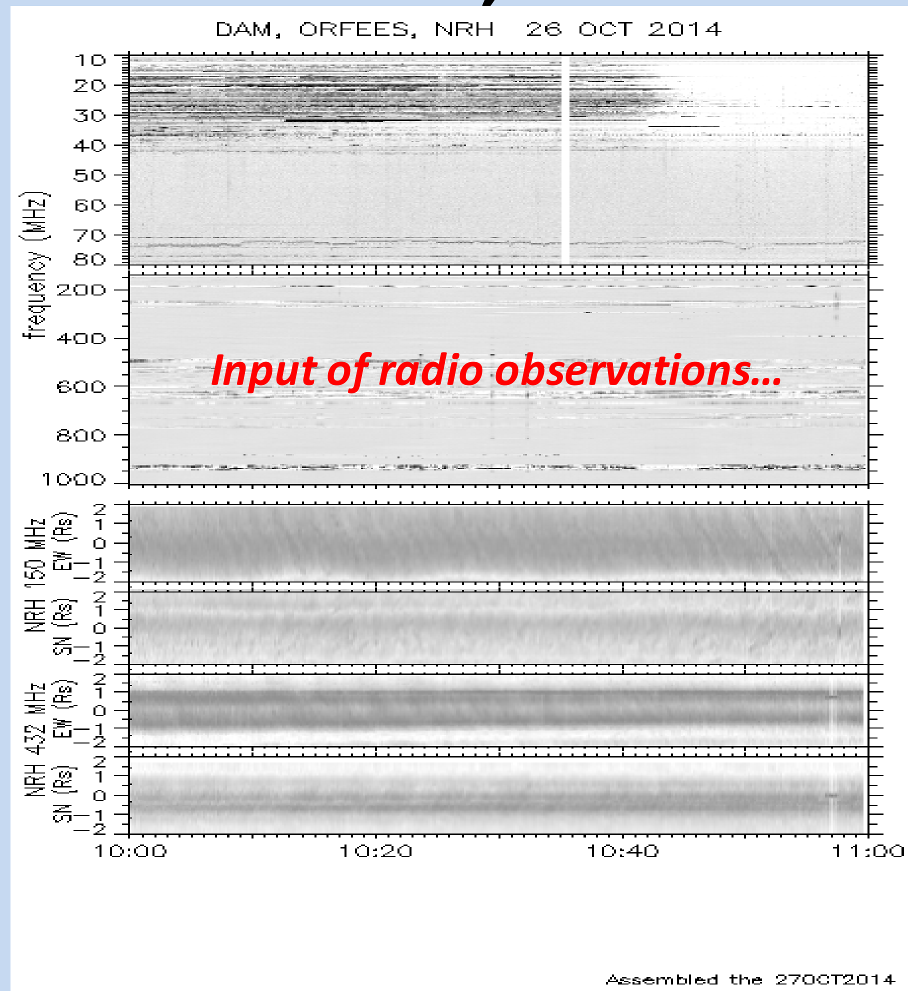
SEP events are preferentially produced by X-class or long duration M class flares

SEP prediction (time history) based on SXR derivative /or radio microwave measurements
Núñez Sp Wea 2011
Zucca et al., JSWSC 2017

How to anticipate/ predict flares and associated events such as CMEs, SEPs?

But see e.g. AR 12192
high flare productivity
low CME productivity,



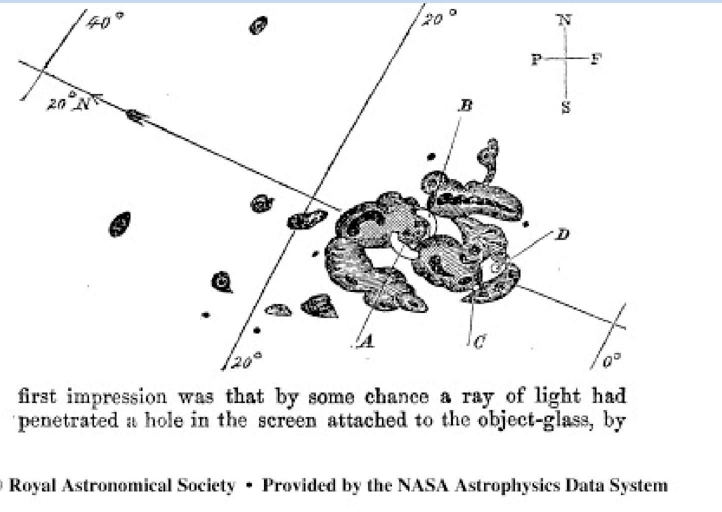


No radio emission in the m/dm domain at the time of the X-ray flare!

WHAT ABOUT EXTREME FLARES ?

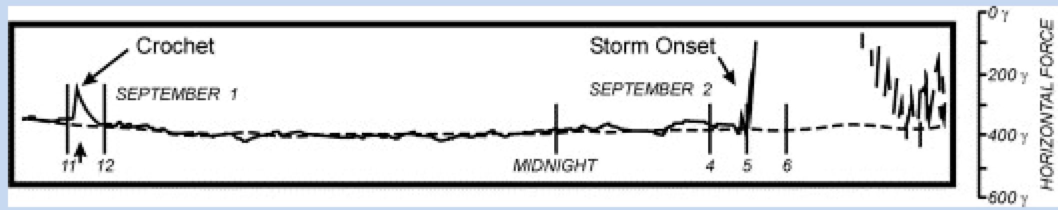
EXTREME EVENTS.

The beginning of solar terrestrial physics: the Carrington flare(1 September 1859)



Carrington, 1860; Hodgson, 1860

Magnetic field observations at Kew (London)
Variations of the horizontal component of the Earth's magnetic fie



Stewart, (1861)

Observation of a « brightening »
1 September 1859 around 11h18
in an extremely large sunspot group

X45 +/- 5 (Cliver & Dietrich, 2013)

Very intense geomagnetic storm
17h40 minutes after the solar flare
Northern ligths visible in Santiago (Chile), Hawai
Extreme event also recorded in Bombay:
telegraph disruptions for many hours
(Tsurutani et al., 2003) (Dst estimated between -800 et -1700

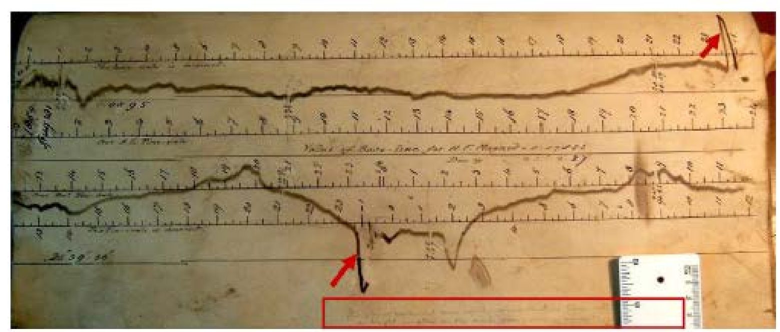
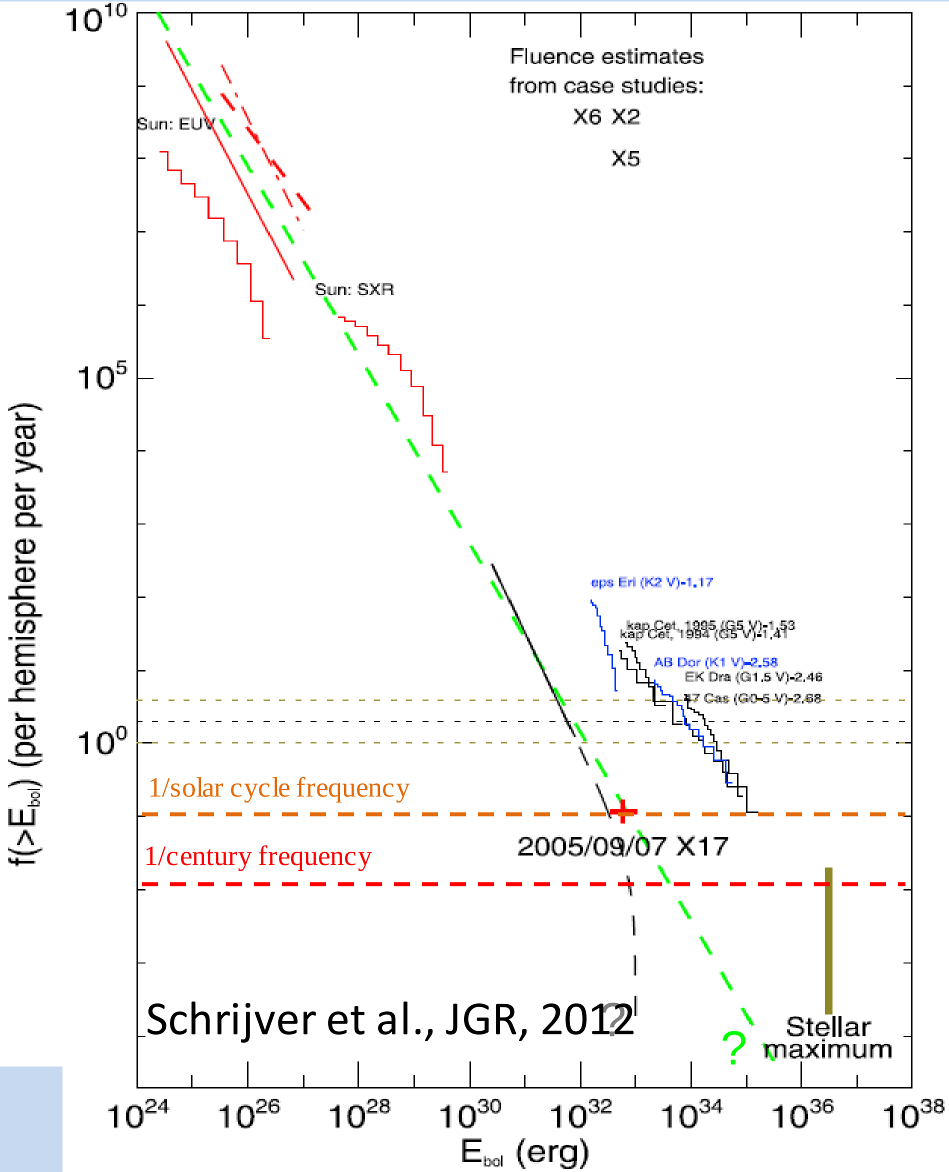


Fig. 1. Greenwich Observatory magnetometer traces (horizontal force on top and declination on the bottom; the two traces are offset by 12 h) during the time of the solar flare on 1 September 1859. The red arrows indicate the magnetic crochet or SFE. The writing at the bottom in the red box says "The above movement was nearly coincidental in time with Carrington's observation of a bright eruption on the Sun. Disc[overed] over a sunspot. (H.W.N., 2 Dec 1938)". H.W.N. refers to Harold W. Newton, Maunder's successor as the sunspot expert at Greenwich. (From Cliver & Keer 2012, with permission of *Solar Physics*.)

Extreme solar flares: How extreme?



How to extrapolate the observed energy distribution of flares?

Can we rely on stellar analogies? > 10^{36} erg

Should we rely on the size of the largest Sunspots observed?

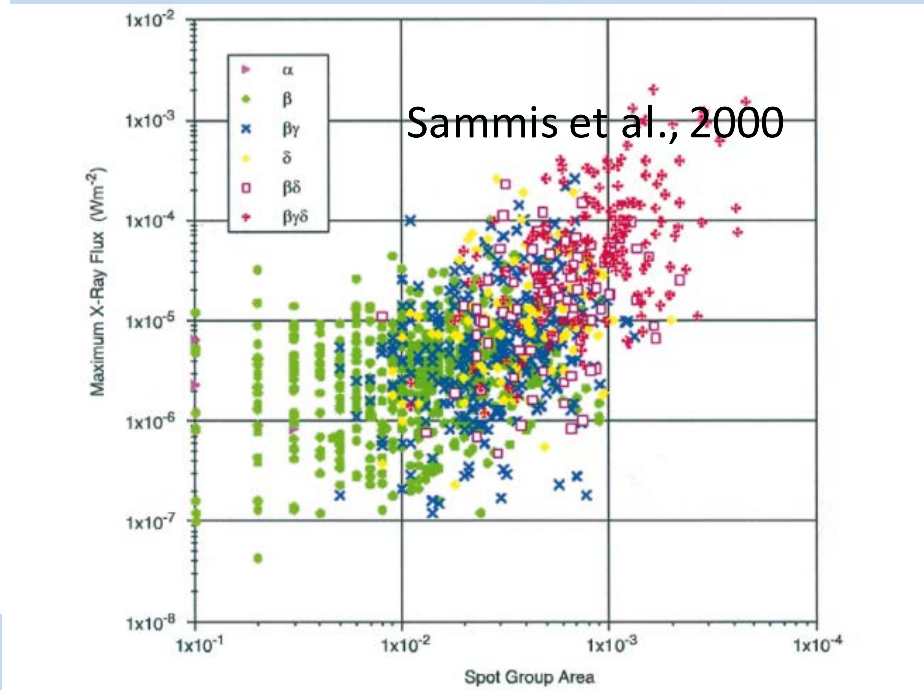
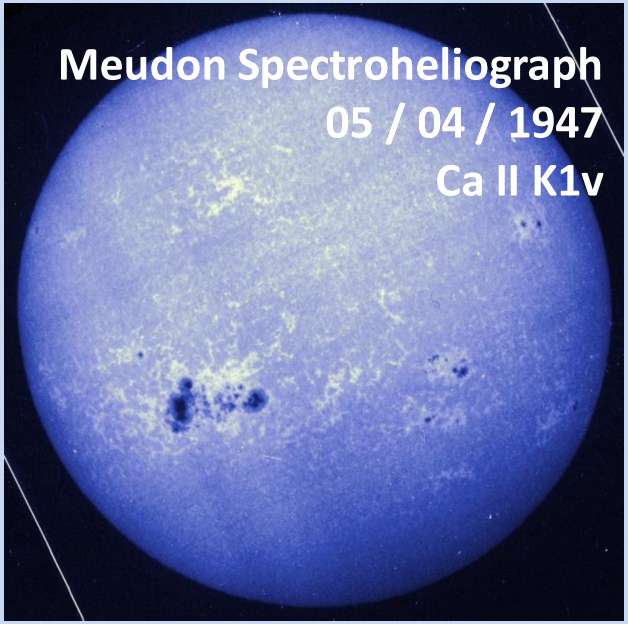


FIG. 2.—Peak flare intensities in W m^{-2} for each spot group as a function of peak area in disk fraction, with each magnetic class plotted separately. Clearly all the big events at upper right occur in δ spots, those classed $\beta\gamma\delta$ by SOON. Regions producing no flares have been omitted.

Extreme solar flares: How extreme?

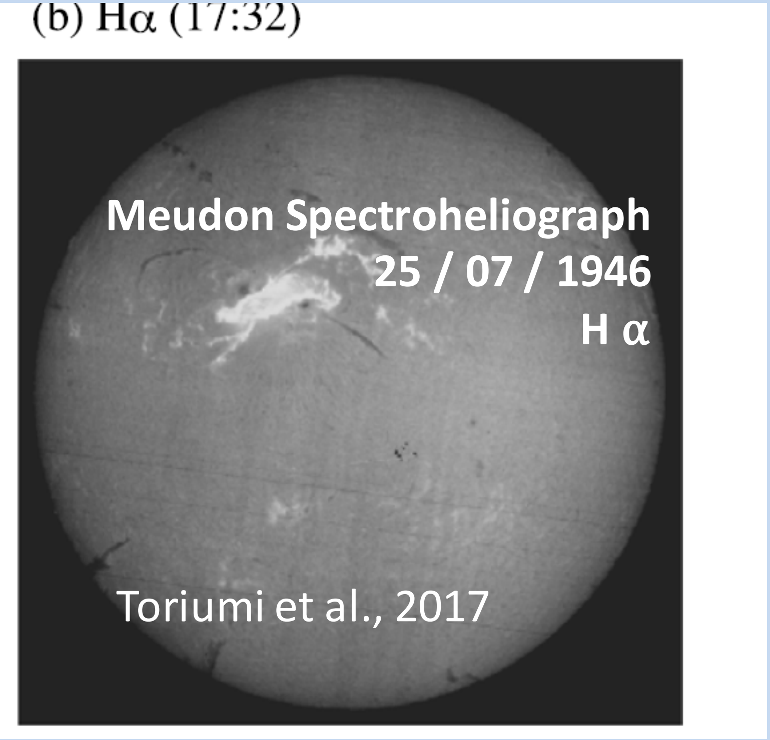


Two methods based on different scalings
To estimate the largest flare energy
from the largest observed size of an AR!
And from the more extended ribbons!

Toriumi et al., 2017: flare energy **up to 10^{34} erg**
Sample of 51 Flares (> M5) from 2010 to 2016
Scaling of the energy released on the AR size, the distance between ribbons,;..

One of the largest sunspot group observed (Aulanier et al., 2013) flare energy: **6 10^{33} erg**
Scaling of the flare energy release with the size of Ars
Based on the results and scaling of MHD simulations

To have a larger flare:
To release more energy from an AR ?
To have interaction between several AR
Energy coming from interconnected ARs?
To concentratre the magnetic flux on a larger single AR?



Extreme solar flares and extreme space weather

A few caveats

Extreme events can occur in the declining or rising phase of the solar cycle (not at the maximum of the sunspot number) (e.g. 23 February 1956 largest SEP event > 1 GeV)

Extreme events do not necessarily generate the complete spectrum of extreme space weather effects (radio blackouts, geomagnetic storms, extreme solar energetic particles)

Extreme solar flares and extreme space weather

A few caveats

Some « non extreme » events such as M-class X-ray flares can be associated with « extreme » radio out bursts causing problems with communications, radars…(4 November 2015, 6 December 2006, …)

Some of these « extreme » events occur in periods where radio communications were strategic: e.g. 23 May 1967 (Knipp et al;, Sp Wea, 2016) colossal radio burst : radio interference at frequencies between 0.01 and 9.0 GHz

8000 sfu at 2.8 GHz (probability of 1% based on statistics of Nita et al. (2002; 2004)
85000 sfu at 1.4 GHz

Origin of these major radio enhancements clearly unknown

Almost impossible to predict if a flare will produce these strong outbursts

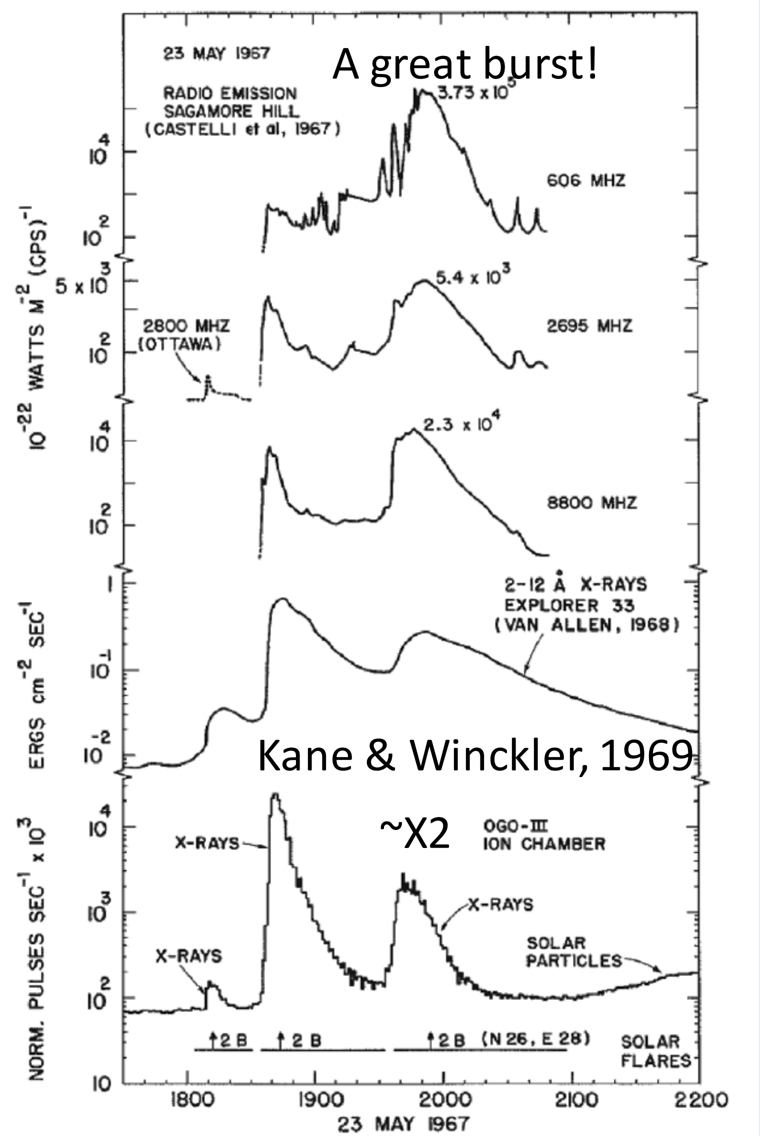


Figure 5. Profiles of solar radio and X-ray emissions on 23 May 1967 from *Kane and Winckler* [1969b]. The interval covers the three primary flares of 23 May 1967. Reprinted with permission from Solar Physics.

How to anticipate flares, and super-flares? Some Conclusions

Why anticipate flares?

- Flares are the first signatures of space-weather events
- Flares can have direct and almost immediate effects (ionization of the earth's atmosphere , strong associated radio outbursts causing interfereneces…)

Is it easy to anticipate flares?

No , predicting solar flares is still very challenging. (no method really allows the forecast of a>M-class flare witha skill score substantially better than climatoligical forecasts (Barnes et al., 2016))

An additional challenge is to be able to predict when the flare will happen, how large it will be, what could be the associated radio out burst…

The task is even more challenging when it comes to the study and prediction of super Flares…(extremely low number of events , low statistics…

Not a large number of extreme events observed in space (since the 1970s)
Need to investigate previously recorded events: interest of archives of continuous Observations recorded for many cycles…

Thank you!