National Weather Service

Space Weather Prediction Center

Investigation of Active Region Properties for Solar Flare Forecasts

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Outline

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- Terminology
  - Solar Flares
  - Active Regions
  - Sunspots
- Classifications
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- Parameters
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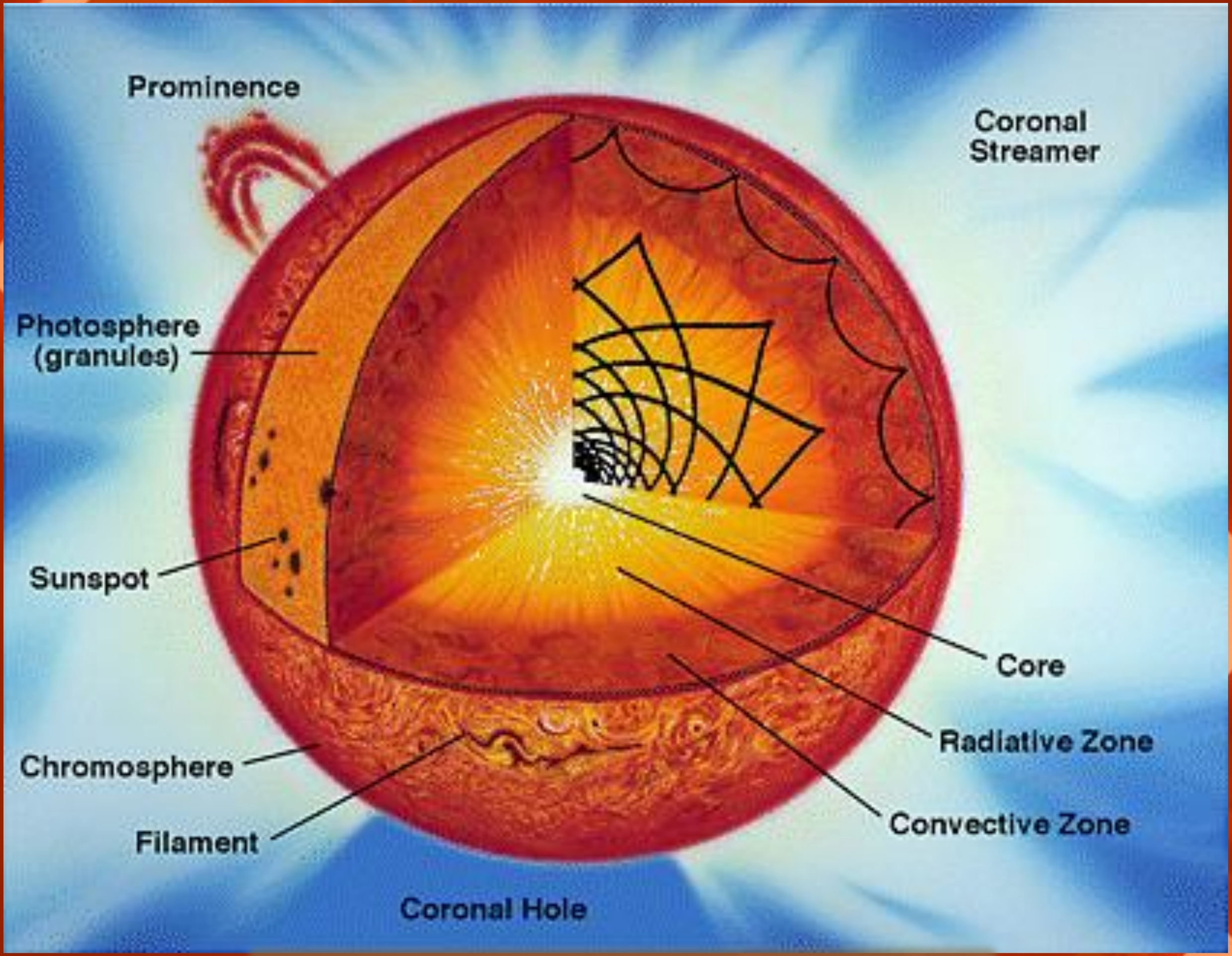
- Conclusion

Goal

My goal is to help improve the way flares are forecasted.

- Space weather events can destroy or interrupt important technology, harm astronauts, and misdirect homing pigeons.

An Introduction to Terminology

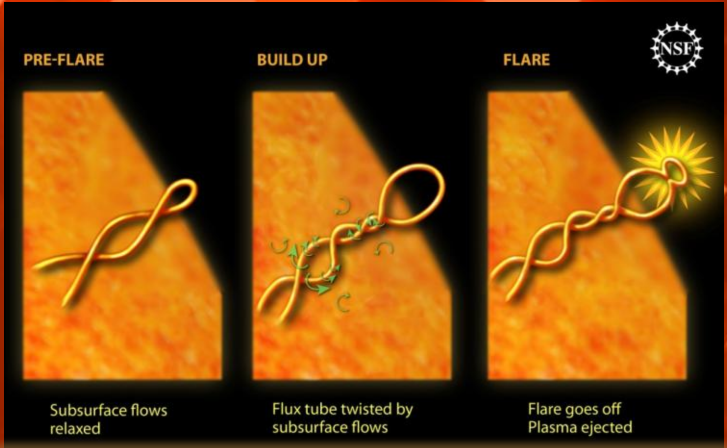


http://lwsde.gsfc.nasa.gov/LWS_Space_Weather/SpaceWeatherOverview.html

What are Solar Flares?

- A sudden release of energy stored in twisted magnetic fields.
- Solar flares are classified according to their x-ray peak wavelength.
  - **X-class flares** are big.
  - **M-class flares** are medium-sized.
  - **C-class flares** are small.

Flare Class	Class Peak (W/m^2) between 1 and 8 Angstroms	Pneumonic
X	$I \geq 10^{-4}$	Xtreme
M	$10^{-5} \leq I < 10^{-4}$	Mediocre
C	$10^{-6} \leq I < 10^{-5}$	Cheesy
B	$I < 10^{-6}$	Baby



http://www.noaanews.noaa.gov/stories2010/20100119_solarflare.html

NOAA Space Weather Scales

Category		Effect	Physical measure	Average Frequency (1 cycle = 11 years)
Scale	Descriptor	Duration of event will influence severity of effects		
Geomagnetic Storms			Kp values* determined every 3 hours	Number of storm events when Kp level was met; (number of storm days)
G 5	Extreme	Power systems: widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. Spacecraft operations: may experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. Other systems: pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.)**.	Kp=9	4 per cycle (4 days per cycle)
G 4	Severe	Power systems: possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. Spacecraft operations: may experience surface charging and tracking problems, corrections may be needed for orientation problems. Other systems: induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.)**.	Kp=8, including a 9-	100 per cycle (60 days per cycle)
G 3	Strong	Power systems: voltage corrections may be required, false alarms triggered on some protection devices. Spacecraft operations: surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may Other systems: intermittent sa radio may be intermittent, and lat.)**.	Kp=7	200 per cycle (130 days per cycle)
G 2	Moderate	Power systems: high-latitude transformer damage. Spacecraft operations: correct drag affect orbit predictions. Other systems: HF radio prop and Idaho (typically 55° geom		
G 1	Minor	Power systems: weak power Spacecraft operations: minor Other systems: migratory ani latitudes (northern Michigan		

* Based on this measure, but other physical measures are also
** For specific locations around the globe, use geomagnetic la

** For specific locations around the globe, use geomagnetic latitude to determine likely sightings (see www.sec.noaa.gov/Aurora)

Solar Radiation Storms			Flux level of ≥ 10 MeV particles (ions)*	Number of events when flux level was met**
S 5	Extreme	Biological: unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. *** Satellite operations: satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. Other systems: complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10^5	Fewer than 1 per cycle
S 4	Severe	Biological: unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** Satellite operations: may experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. Other systems: blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^4	3 per cycle
S 3	Strong	Biological: radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** Satellite operations: single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. Other systems: degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3	10 per cycle
S 2	Moderate	Biological: passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk.*** Satellite operations: infrequent single-event upsets possible. Other systems: effects on HF propagation through the polar regions, and navigation at polar cap locations possibly affected.	10^2	25 per cycle
S 1	Minor	Biological: none. Satellite operations: none. Other systems: minor imp	10	50 per cycle

* Flux levels are 5 minute averages. Flux in particles·s⁻¹·
** These events can last more than one day.
*** High energy particle measurements (>100 MeV) are a b

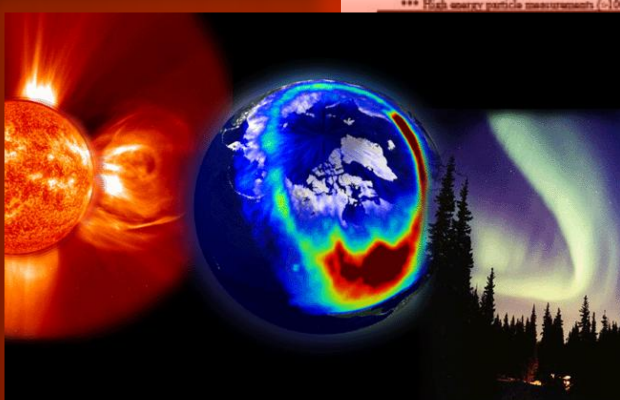
*** High energy particle measurements (>100 MeV) are a better indicator of radiation risk to passenger and crews. Pregnant women are particularly susceptible.

Radio Blackouts			GOES X-ray peak brightness by class and by flux*	Number of events when flux level was met; (number of storm days)
R 5	Extreme	HF Radio: Complete HF (high frequency**) radio blackout on the entire sunlit side of the Earth lasting for a number of hours. This results in no HF radio contact with mariners and en route aviators in this sector. Navigation: Low-frequency navigation signals used by maritime and general aviation systems experience outages on the sunlit side of the Earth for many hours, causing loss in positioning. Increased satellite navigation errors in positioning for several hours on the sunlit side of Earth, which may spread into the night side.	X20 ($2x10^{-3}$)	Fewer than 1 per cycle
R 4	Severe	HF Radio: HF radio communication blackout on most of the sunlit side of Earth for one to two hours. HF radio contact lost during this time. Navigation: Outages of low-frequency navigation signals cause increased error in positioning for one to two hours. Minor disruptions of satellite navigation possible on the sunlit side of Earth.	X10 (10^{-3})	8 per cycle (8 days per cycle)
R 3	Strong	HF Radio: Wide area blackout of HF radio communication, loss of radio contact for about an hour on sunlit side of Earth. Navigation: Low-frequency navigation signals degraded for about an hour.	X1 (10^{-4})	175 per cycle (140 days per cycle)
R 2	Moderate	HF Radio: Limited blackout of HF radio communication on sunlit side, loss of radio contact for tens of minutes. Navigation: Degradation of low-frequency navigation signals for tens of minutes.	M5 ($5x10^{-5}$)	350 per cycle (300 days per cycle)
R 1	Minor	HF Radio: Weak or minor degradation of HF radio communication on sunlit side, occasional loss of radio contact. Navigation: Low-frequency navigation signals degraded for brief intervals.	M1 (10^{-5})	2000 per cycle (950 days per cycle)

* Flux, measured in the 0.1-0.8 nm range, in $W \cdot m^{-2}$. Based on this measure, but other physical measures are also considered.
** Other frequencies may also be affected by these conditions.

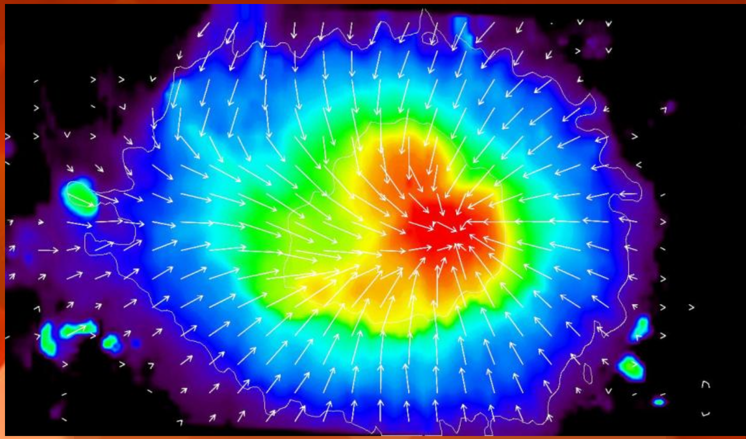
URL: www.sec.noaa.gov/NOAAScales

March 1, 2005



What is an Active Region?

- A part of the solar atmosphere where you can observe:
  - sunspots
  - faculae
  - flares
- Active regions are the result of enhanced magnetic fields.
- Will use interchangeably with “sunspot.”

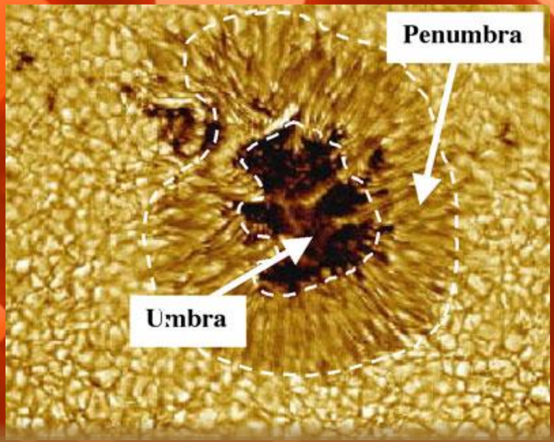


Magnetic gradient field of sunspot

http://www.aip.de/image_archive/Sun.Sunspots.html

What are sunspots?

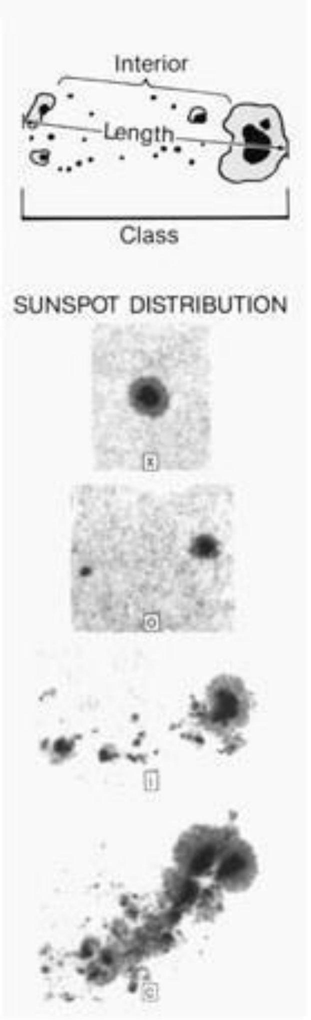
- An area seen as a dark spots on the photosphere of the Sun.
  - Concentrations of magnetic flux.
  - Appear dark because they are cooler than the surrounding photosphere.
  - Larger and darker sunspots sometimes are surrounded (completely or partially) by penumbrae. The dark centers are umbrae.
- Classification
  - The Modified Zurich Sunspot Classification System
  - Devised by McIntosh
  - White-light characteristics of a sunspot group.
  - A 3-letter designation: Zpc



http://www.astrosociety.org/education/publications/tnl/68/solar.html

Classification of Sunspots: Compactness

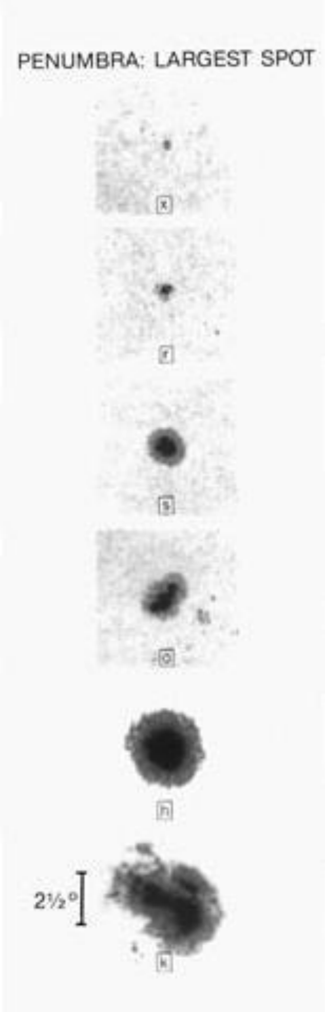
- c:
  - x: a single spot
  - o: open
  - i: intermediate
  - c: compact



http://www.petermeadows.com/html/glossary.html

Classification of Sunspots: Penumbra

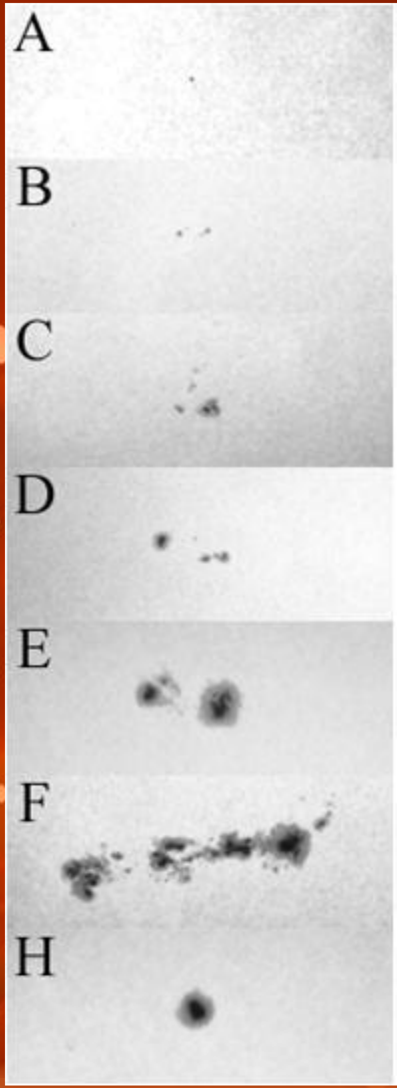
- p:
  - x: no penumbra
  - r: rudimentary
  - s: small (<2.5 degrees north-south diameter), symmetric
  - a: small, asymmetric
  - h: large (>2.5 degrees north-south diameter), symmetric
  - k: large, asymmetric



http://www.petermeadows.com/html/glossary.html

Classification of Sunspots: Modified Zurich Classification

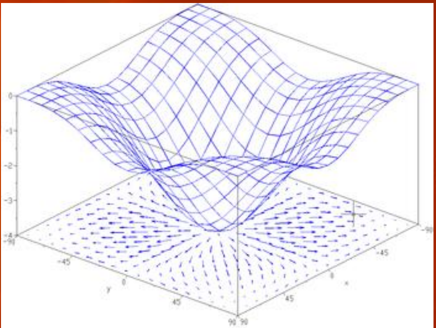
- Z:
  - A:
    - small single sunspot or very small group of spots
    - same magnetic polarity
    - no penumbra
  - B:
    - bipolar
    - no penumbra
  - C:
    - elongated
    - bipolar sunspot group
    - one sunspot must have a penumbra
    - penumbra longitudinal extent < 5°
  - D:
    - elongated
    - bipolar sunspot group
    - penumbra on both ends of the group
    - 5° < Penumbra longitudinal extent < 10°
  - E:
    - elongated
    - bipolar sunspot group
    - penumbra on both ends.
    - 10° < penumbra longitudinal extent < 15°
  - F:
    - elongated
    - bipolar sunspot group
    - penumbra on both ends
    - 15°.< penumbra longitudinal extent
  - H:
    - uni-polar sunspot group
    - with penumbra



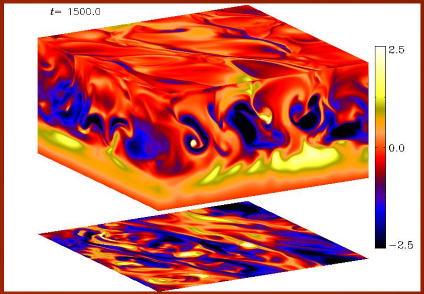
http://solarwww.mtk.nao.ac.jp/en/gallery.html

Some Other Factors

- Helicity
  - The amount of twist in the plasma flow below the surface of the Sun.
  - NOT magnetic helicity
  - IS hydrodynamic helicity

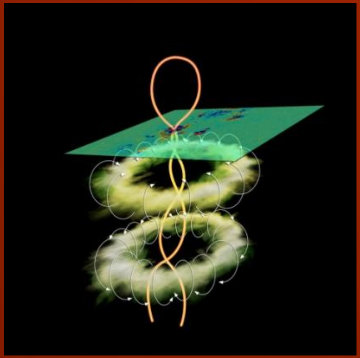


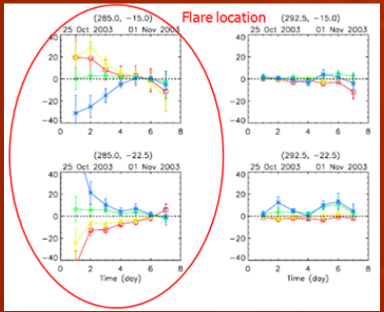
http://www.absoluteastronomy.com/topics/Gradient



http://www.nordita.org/~brandenb/highlights/recent.html

$$H = \int \mathbf{u} \cdot (\nabla \times \mathbf{u}) \; d^3\mathbf{r}.$$

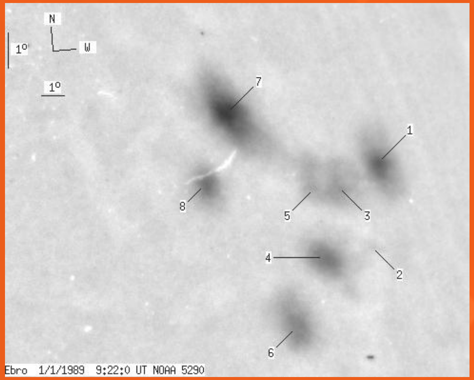




- Normalized Helicity Gradient Variance (NHGV)
  - A parameter designed to capture the large, shrinking spread of helicity values, the overall range of helicity values, and the depth variation of the helicity.

Some Other Factors

- Number of Spots



- Area of Sunspot Group

$$A_M = \frac{A_s 10^6}{2\pi R^2 \cos(B)\cos(L - L_0)}$$

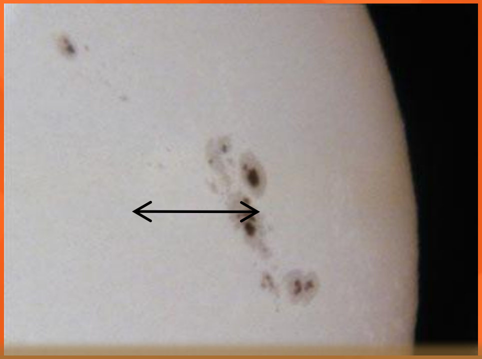
  - A_M=sunspot area in millionths of the sun's visible hemisphere
  - A_S= measured sunspot area (square millimeters or inches)
  - R=radius of solar drawing
  - B=heliographic latitude of sunspot group (degrees)
  - L=heliographic longitude of sunspot group (degrees)
  - L_0=heliographic longitude of the center of the disk (degrees)

- Distance

$$\gamma = \cos^{-1}(\cos\theta_1 \cos\theta_2 + \sin\theta_1 \sin\theta_2 \cos(\phi_1 - \phi_2))$$

  - Subroutine that I wrote
  - Co-latitudes (90-latitude)
  - Degrees to radians
  - Spherical geometry
  - Angle times solar radius to get arc distance between sunspots

- Longitudinal Extent

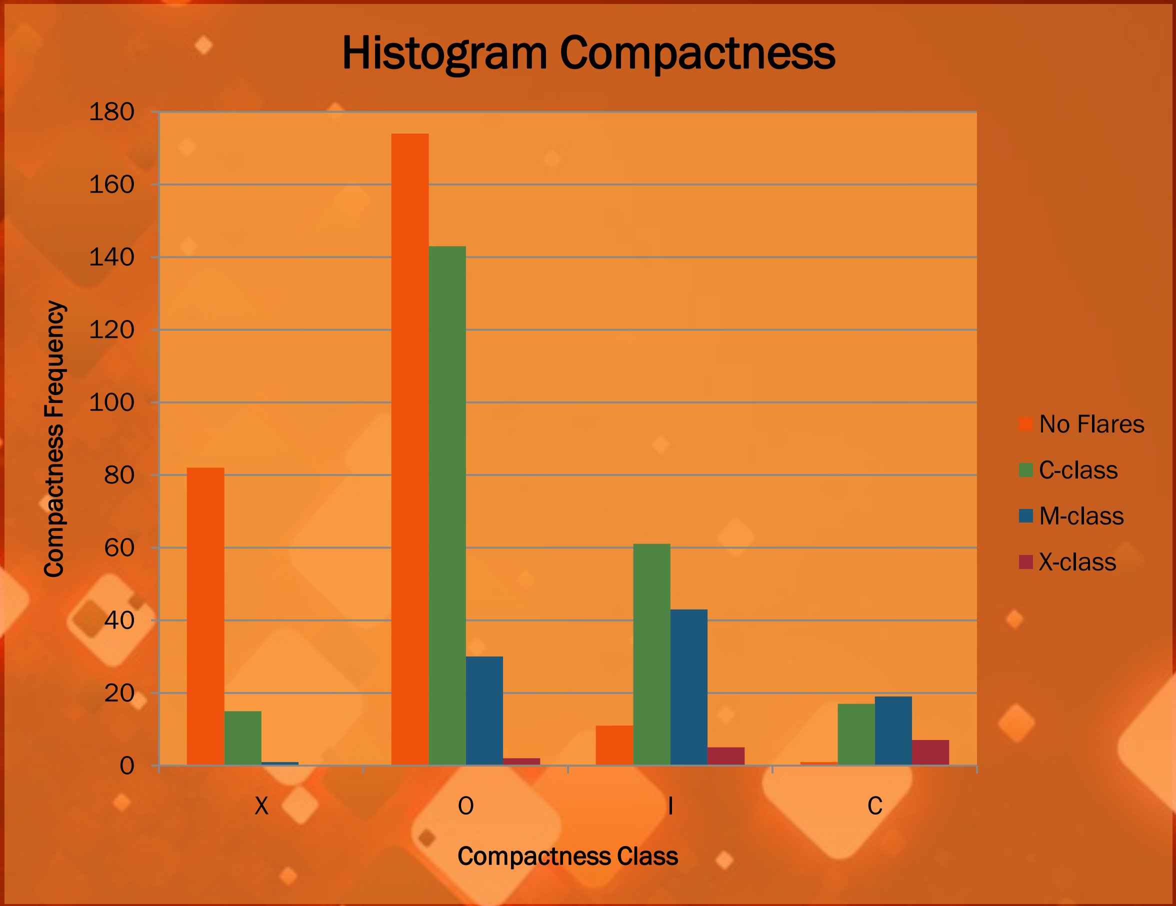


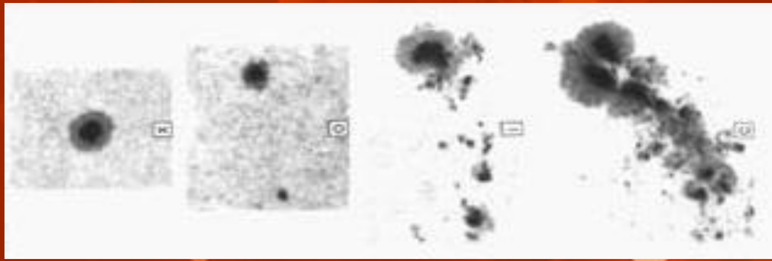
http://www.ne.jp/asahi/stellar/scenes/moon_e/sun2001.htm

What I did

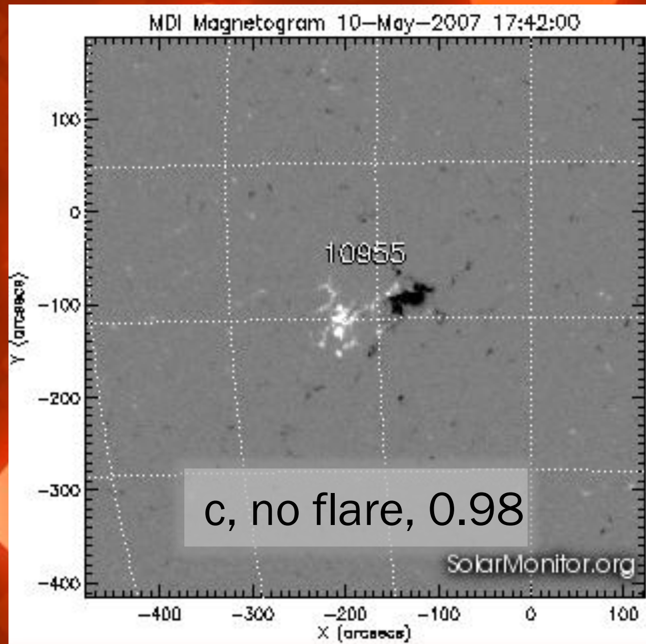
- Pieced together a IDL programs
- Wrote an IDL program to
  - measure distance between two active regions and
  - restrict the location of the sunspot to the center of the disk to avoid uncertainties
- Organized lots of data
- Made lots of plots and histograms
- Looked for patterns with respect to NHGV values in the plots and histograms

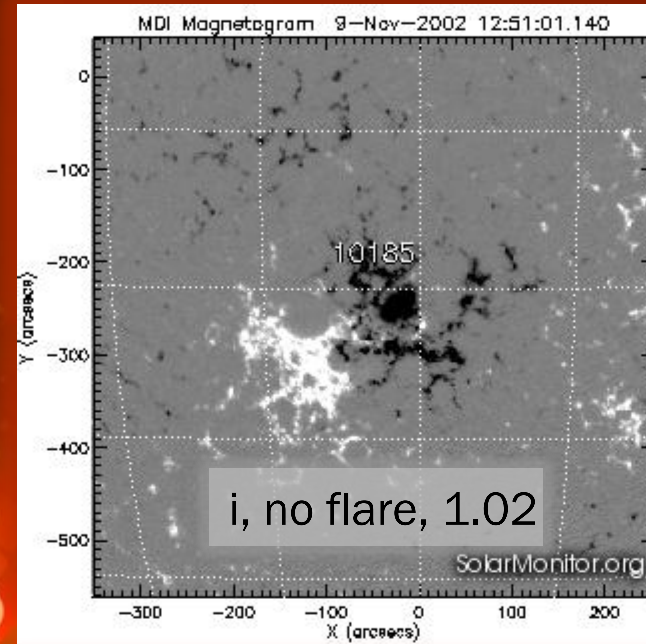
Cool Plots, Results, and Analysis

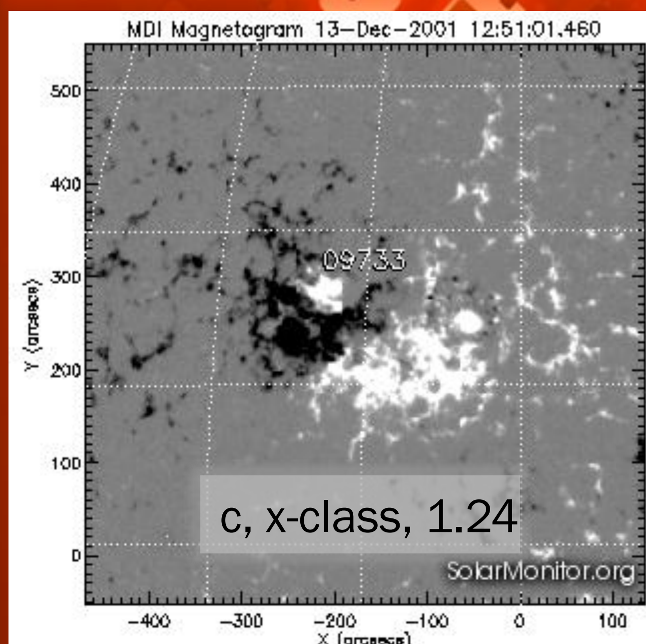


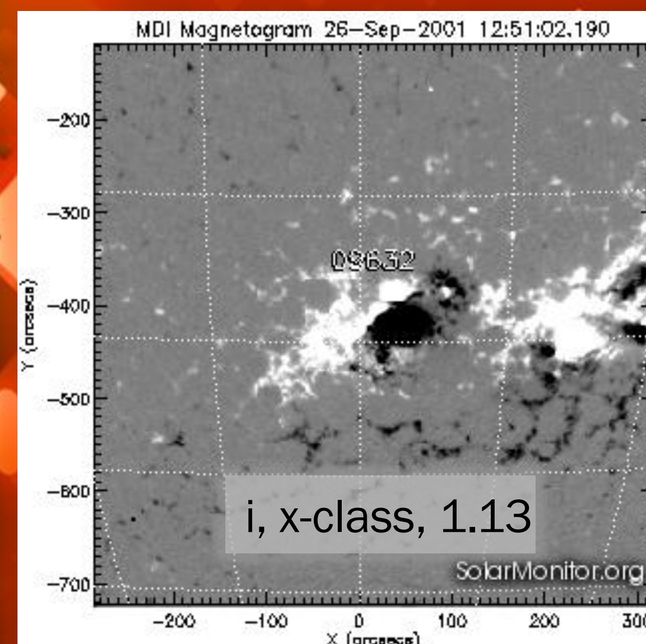


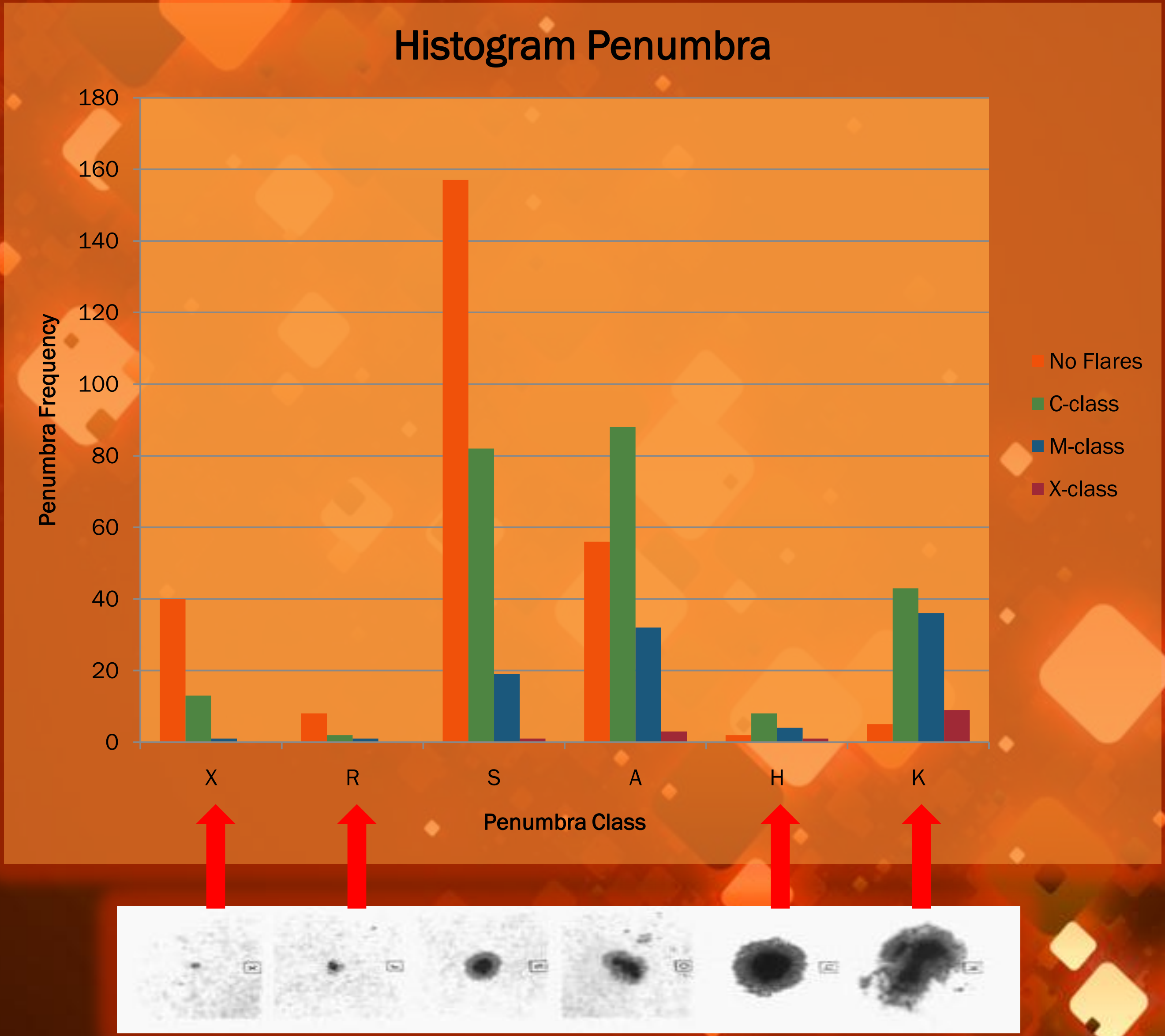
Compactness





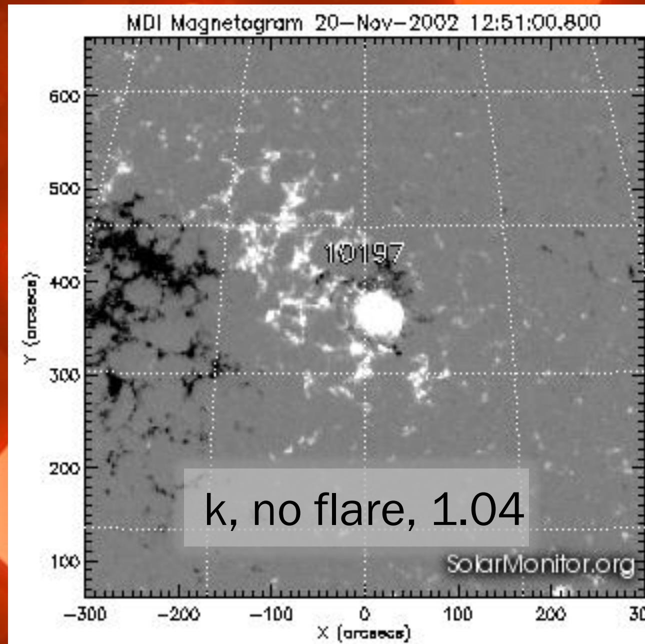


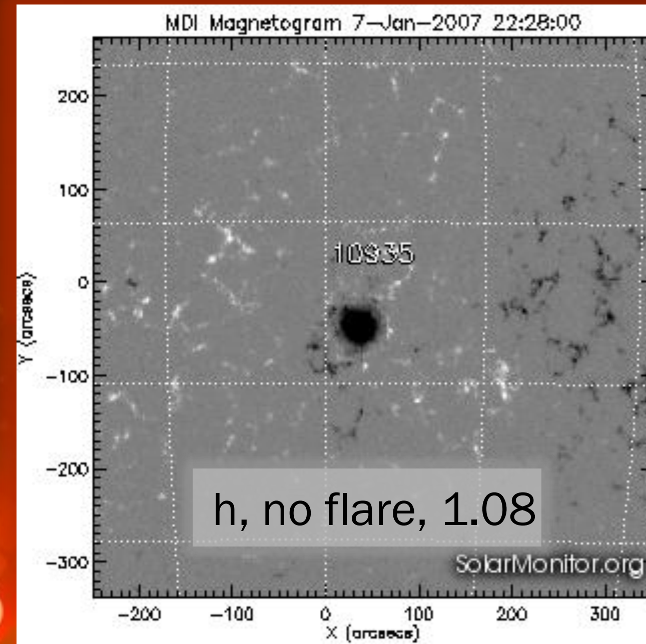




Histogram Penumbra
Penumbra Frequency
180
160
140
120
100
80
60
40
20
0
X
R
S
A
H
K
Penumbra Class
No Flares
C-class
M-class
X-class

Penumbra


MDI Magnetogram 20–Nov–2002 12:51:00.800
10197
k, no flare, 1.04
SolarMonitor.org
X (arcsecs)
Y (arcsecs)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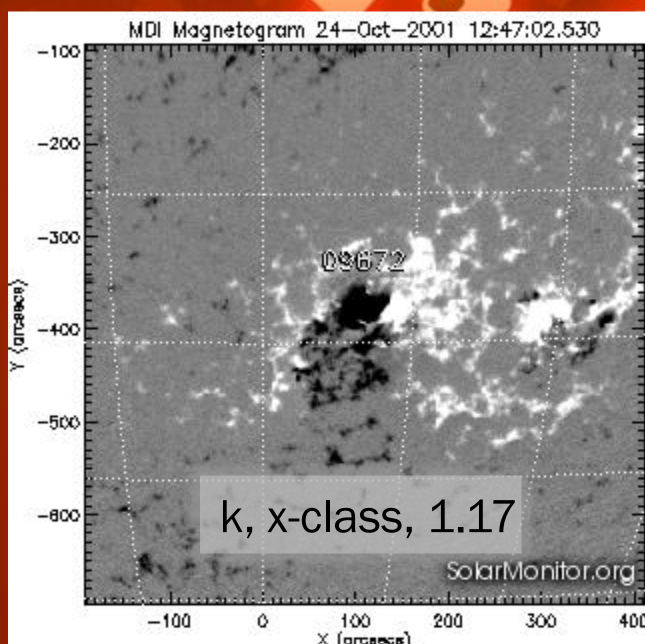
SolarMonitor.org
X (arcsecs)
Y (arcsecs)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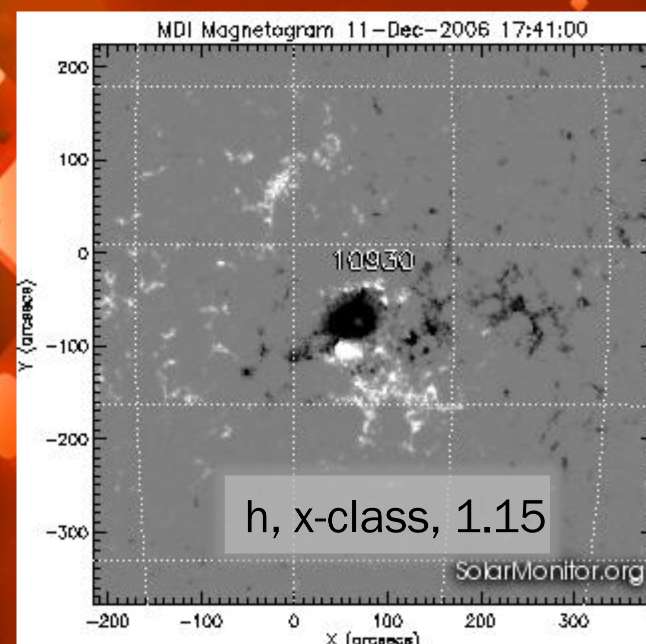
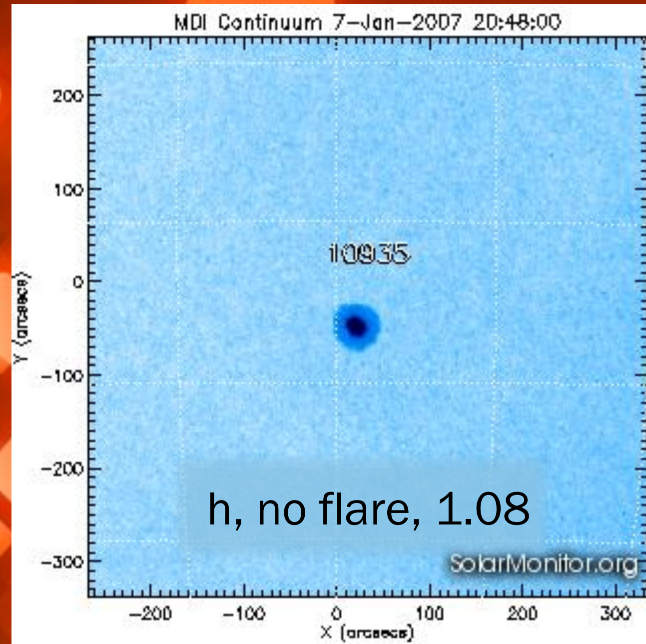
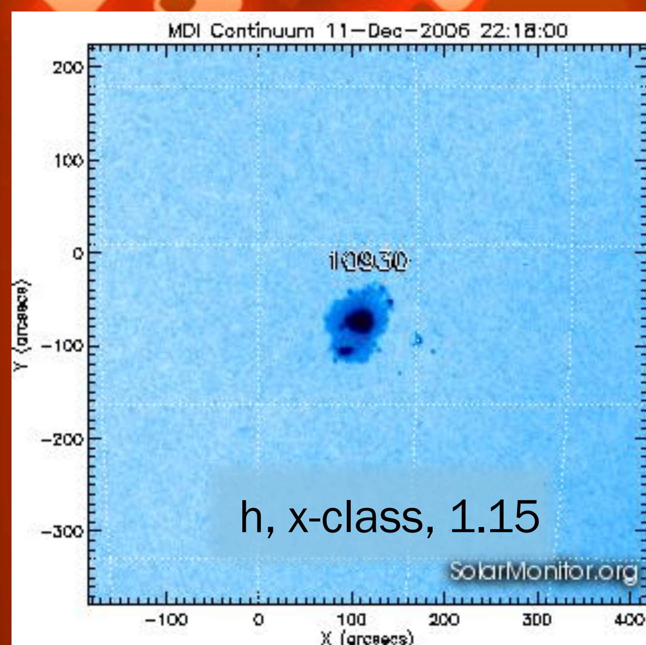
09672
k, x-class, 1.17
SolarMonitor.org
X (arcsecs)
Y (arcsecs)

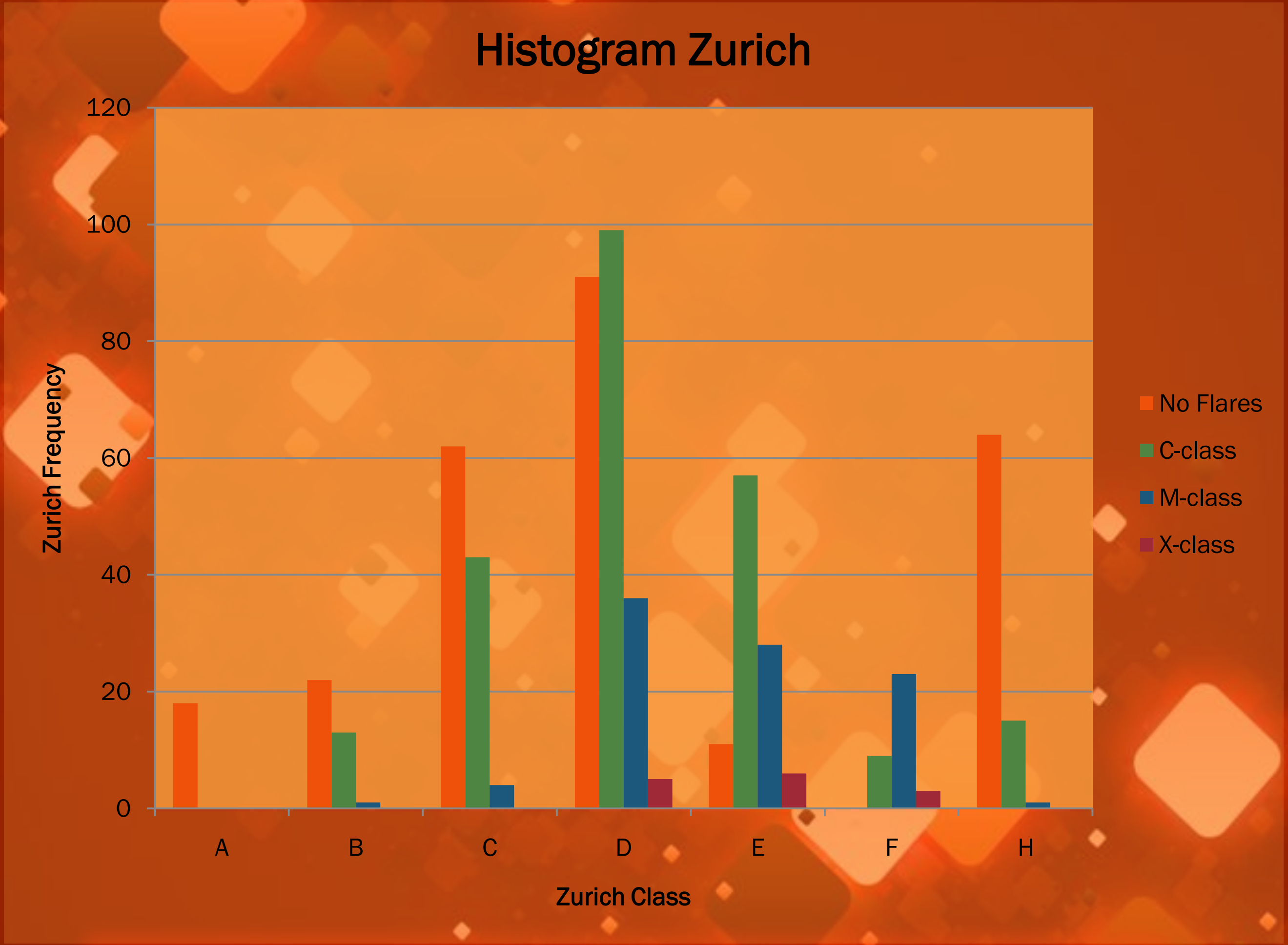

MDI Magnetogram 11–Dec–2006 17:41:00
10930
h, x-class, 1.15
SolarMonitor.org
X (arcsecs)
Y (arcsecs)

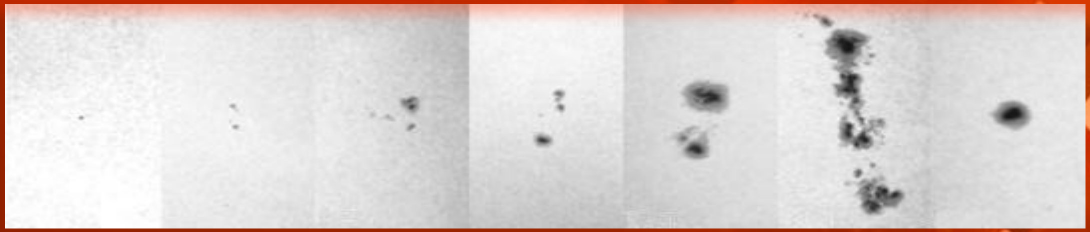
Penumbra

Penumbra

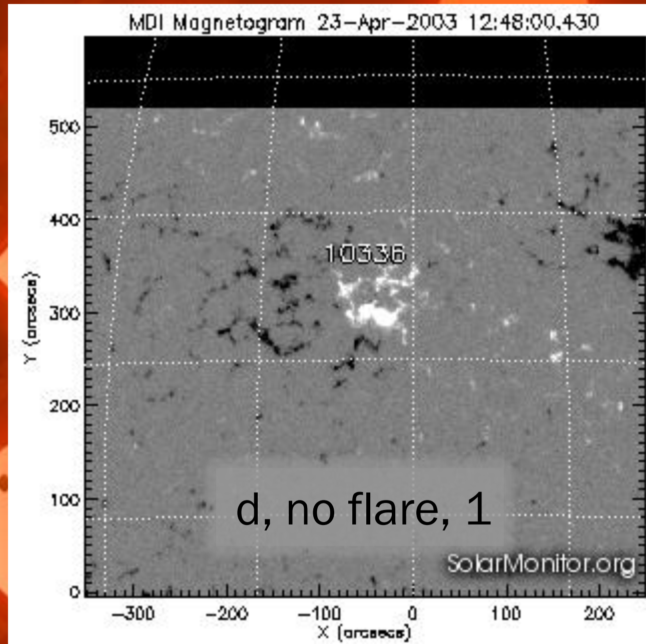





Histogram Zurich
Zurich Frequency
120
100
80
60
40
20
0
A
B
C
D
E
F
H
Zurich Class
No Flares
C-class
M-class
X-class



Zurich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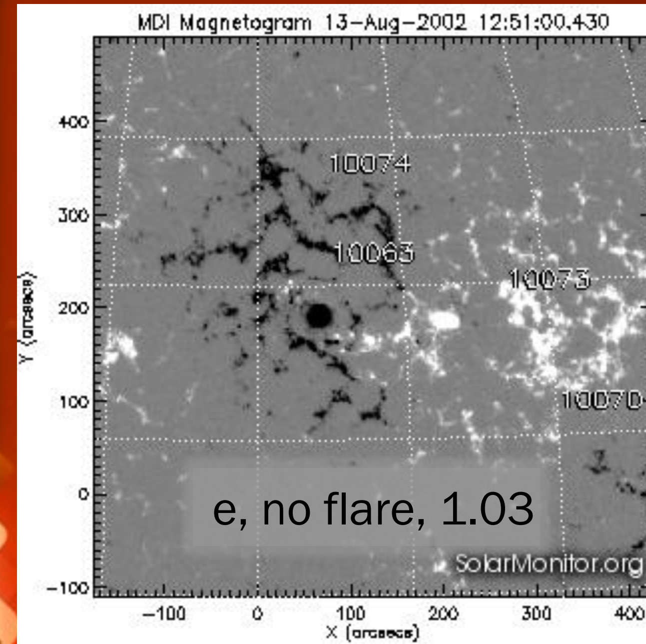
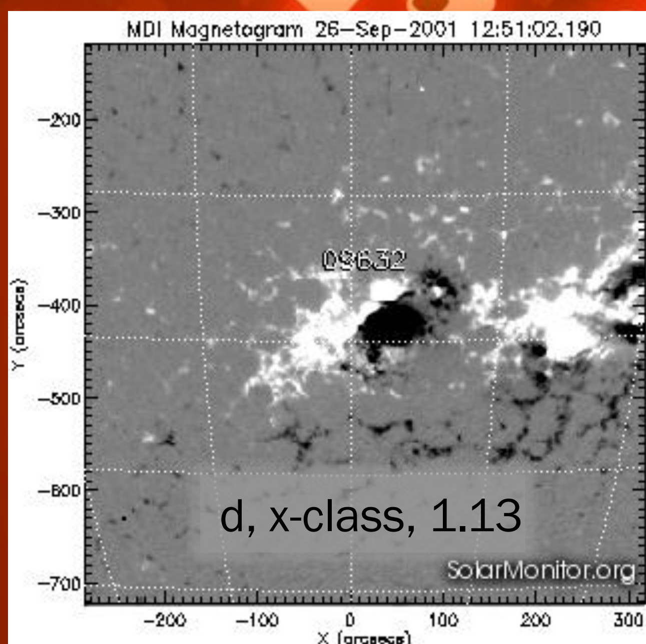
10336
d, no flare, 1
SolarMonitor.org


MDI Magnetogram 13-Aug-2002 12:51:00.430
10074
10063
10073
10070
e, no flare, 1.03
SolarMonitor.org


MDI Magnetogram 26-Sep-2001 12:51:02.190
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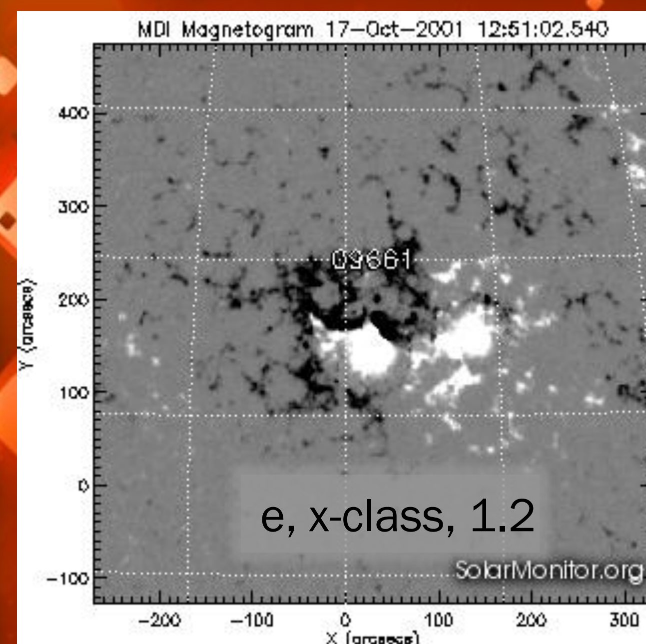
SolarMonitor.org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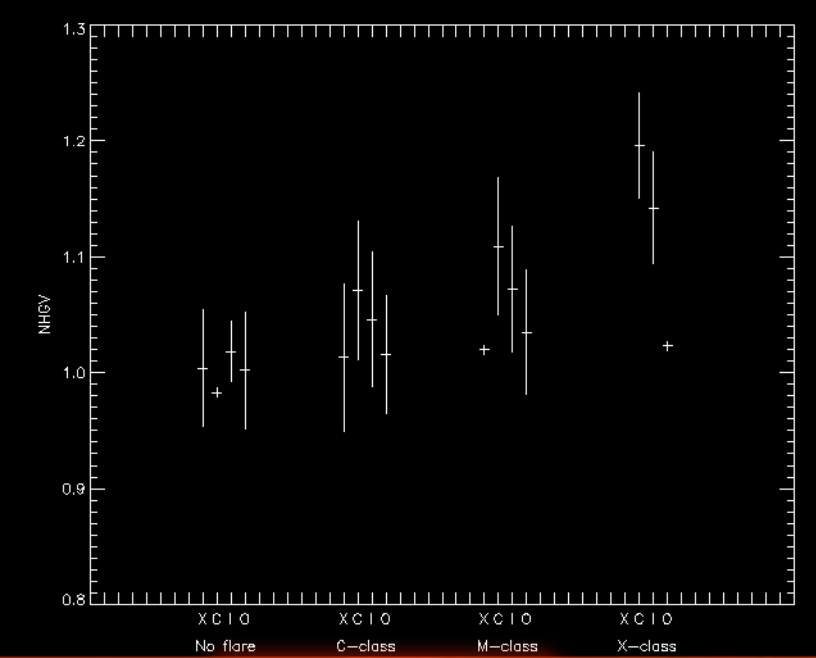
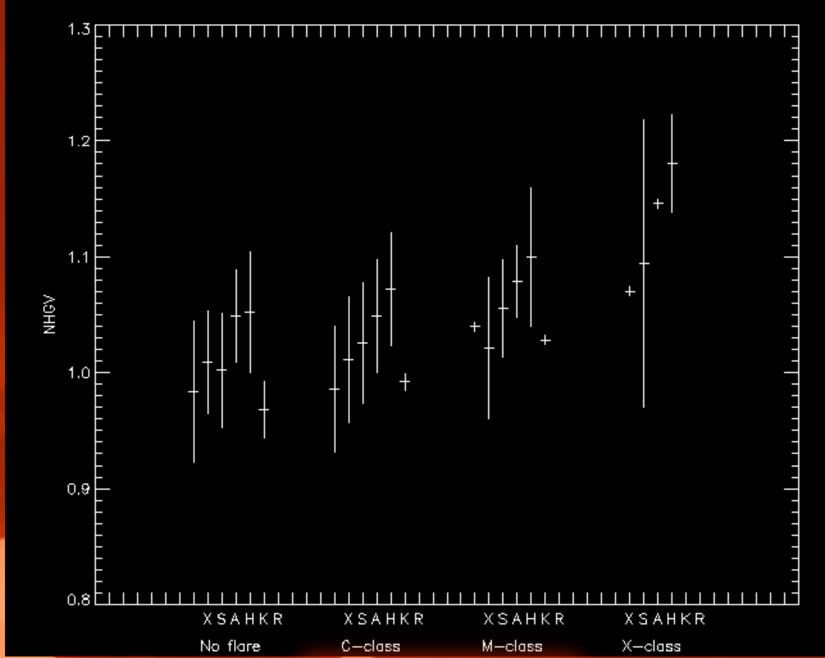
e, x-class, 1.2
SolarMonitor.org



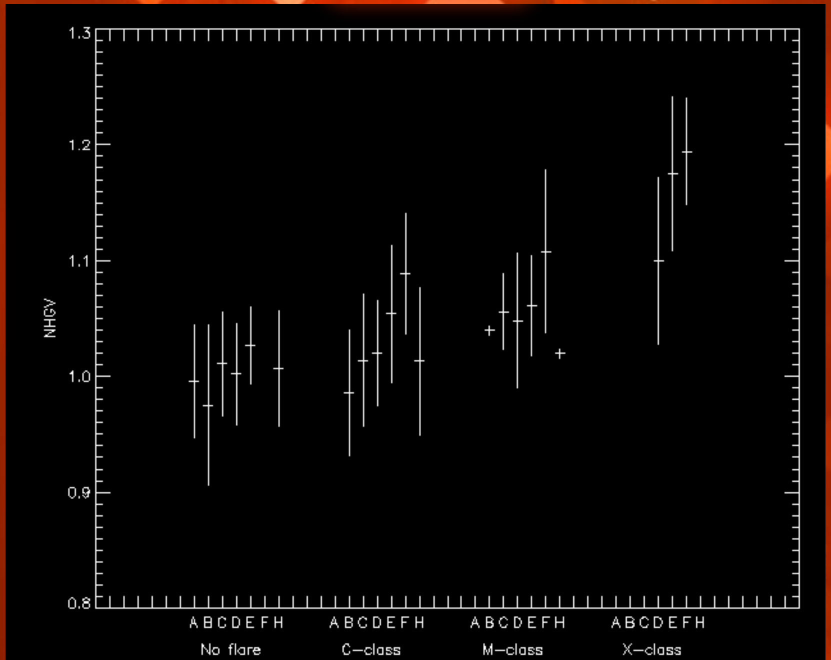


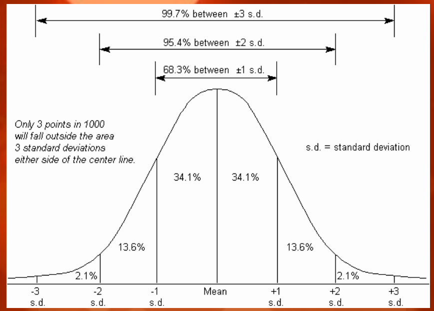
Compactness

Zurich

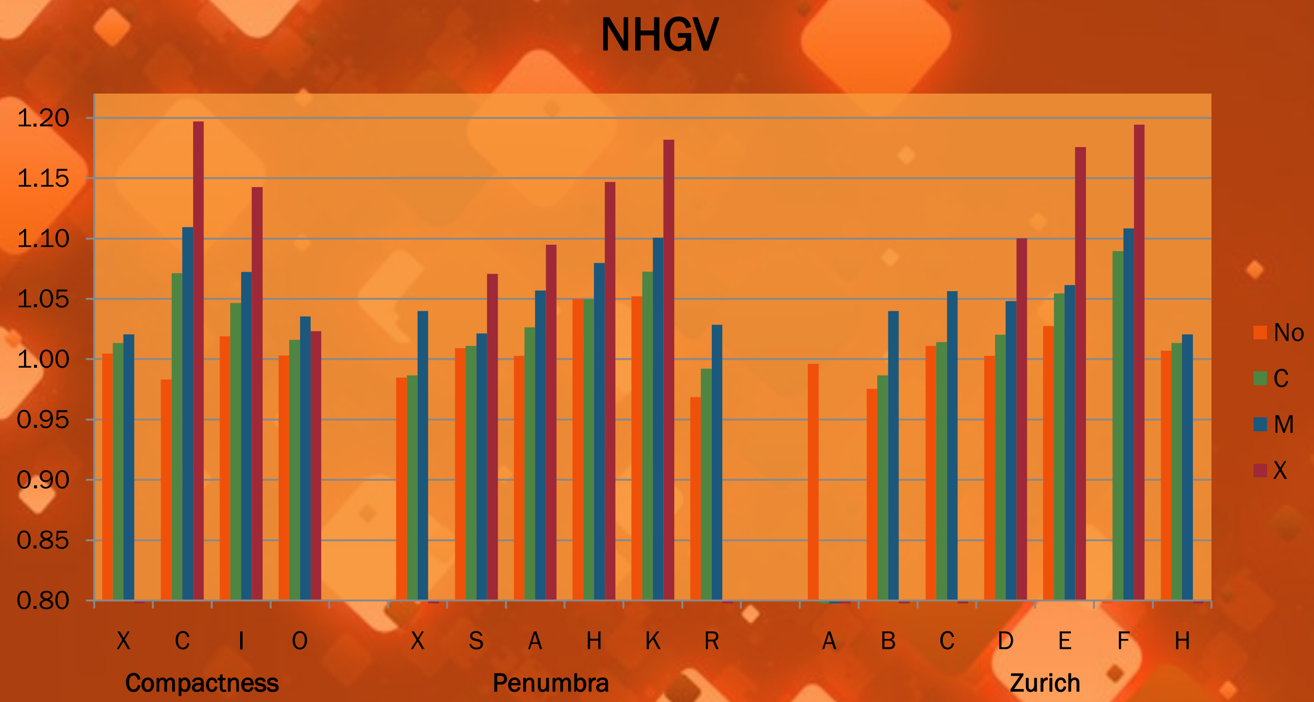
Penumbra

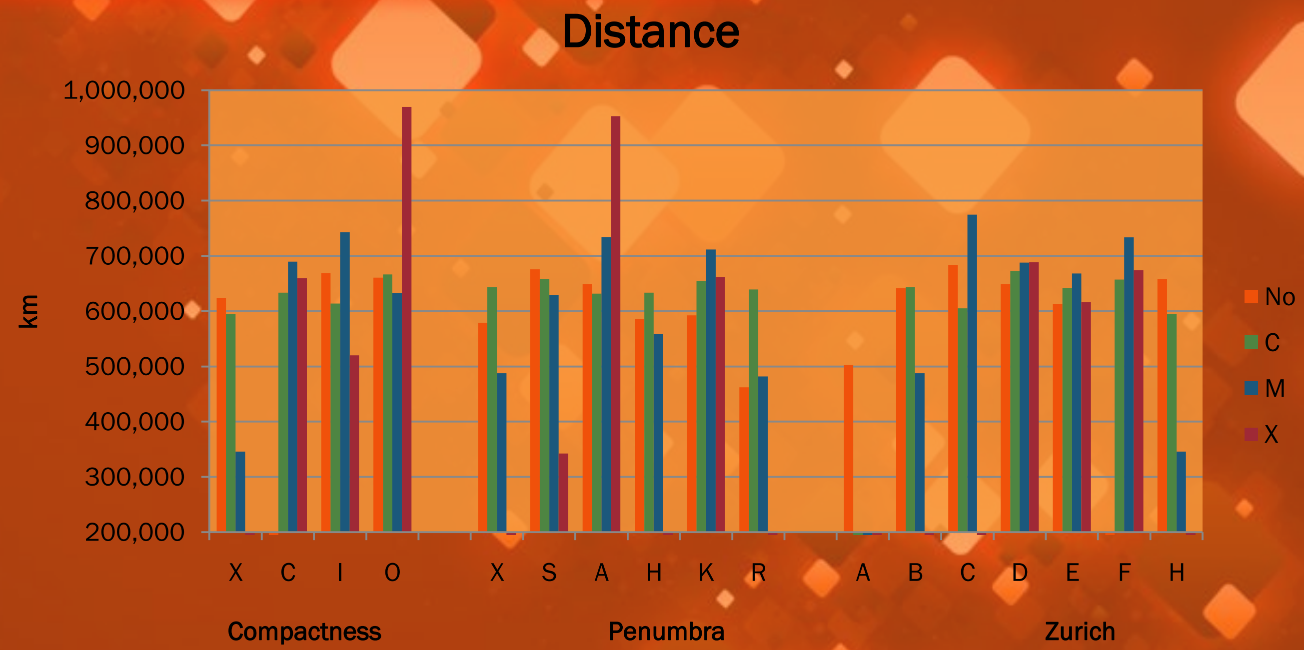
Standard Deviation shows how much variation there is from the average.

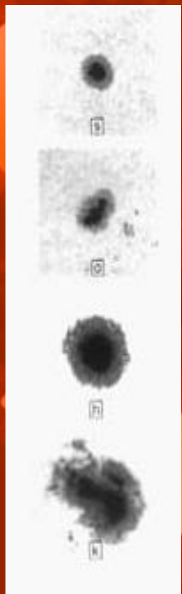


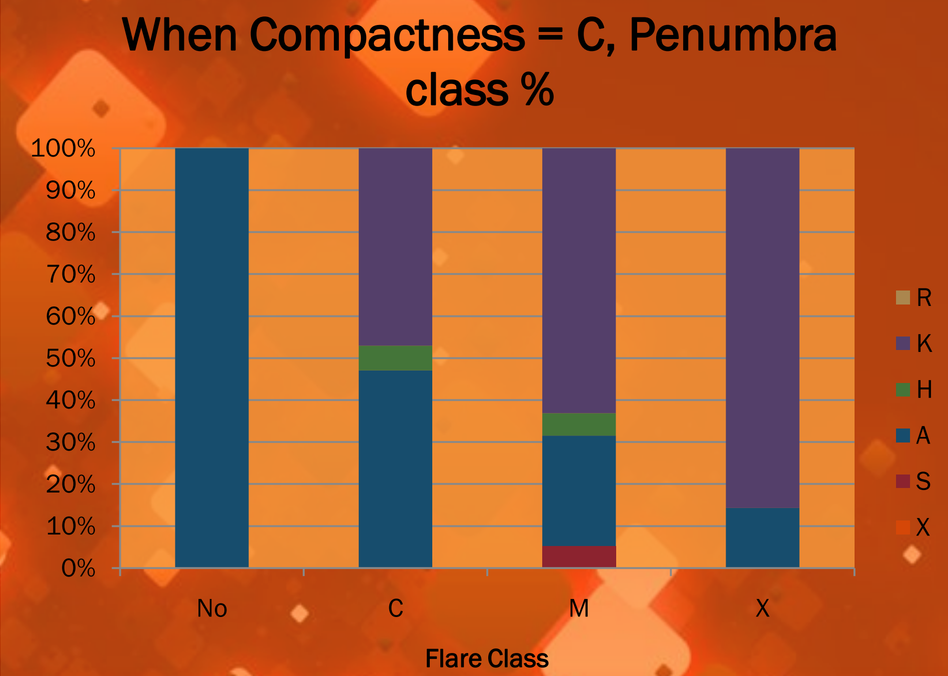


http://www.syque.com/improvement/Standard%20Deviation.htm


NHGV
1.20
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.80
X C I O X S A H K R A B C D E F H
Compactness
Penumbra
Zurich
No
C
M
X


Distance
1,000,000
900,000
800,000
700,000
600,000
500,000
400,000
300,000
200,000
km
X C I O X S A H K R A B C D E F H
Compactness
Penumbra
Zurich
No
C
M
X




When Compactness = C, Penumbra class %
100%
90%
80%
70%
60%
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30%
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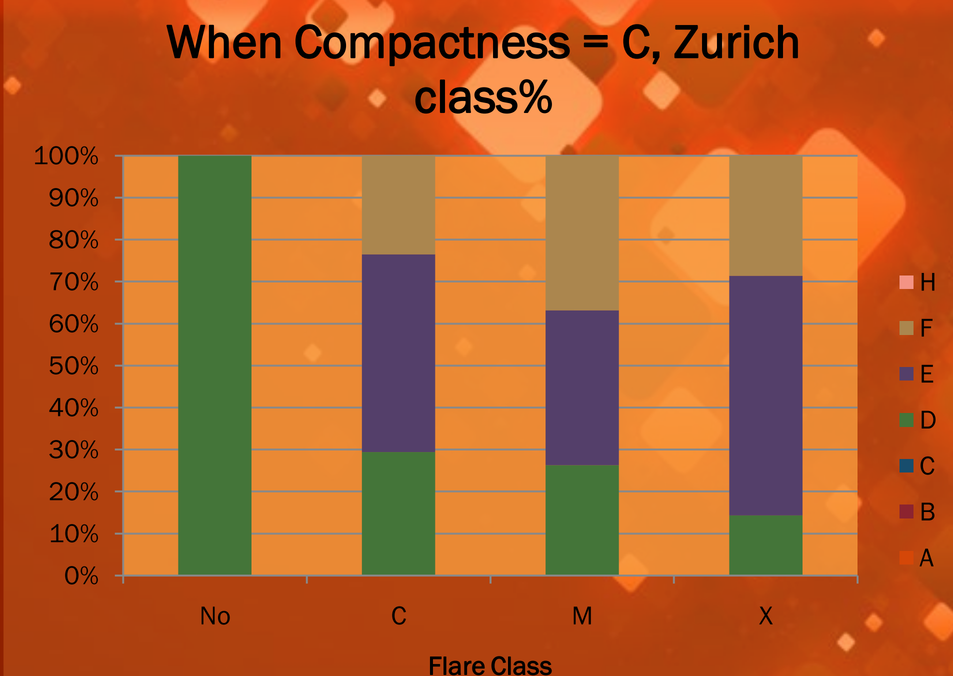
No
C
M
X
Flare Class
R
K
H
A
S
X


When Compactness = C, Zurich class%
100%
90%
80%
70%
60%
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C
M
X
Flare Class
H
F
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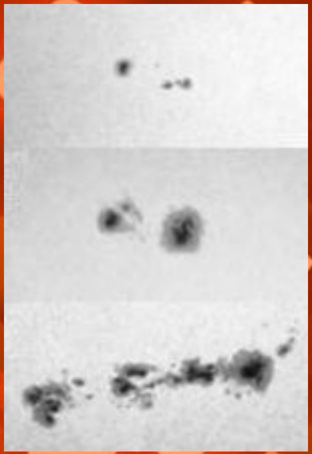
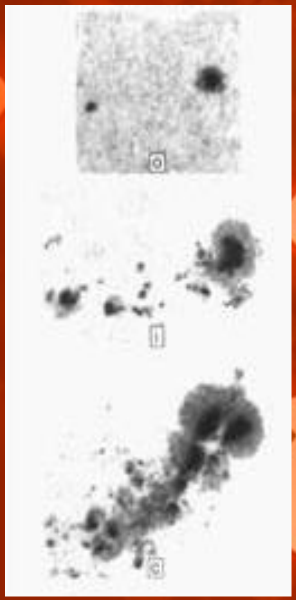
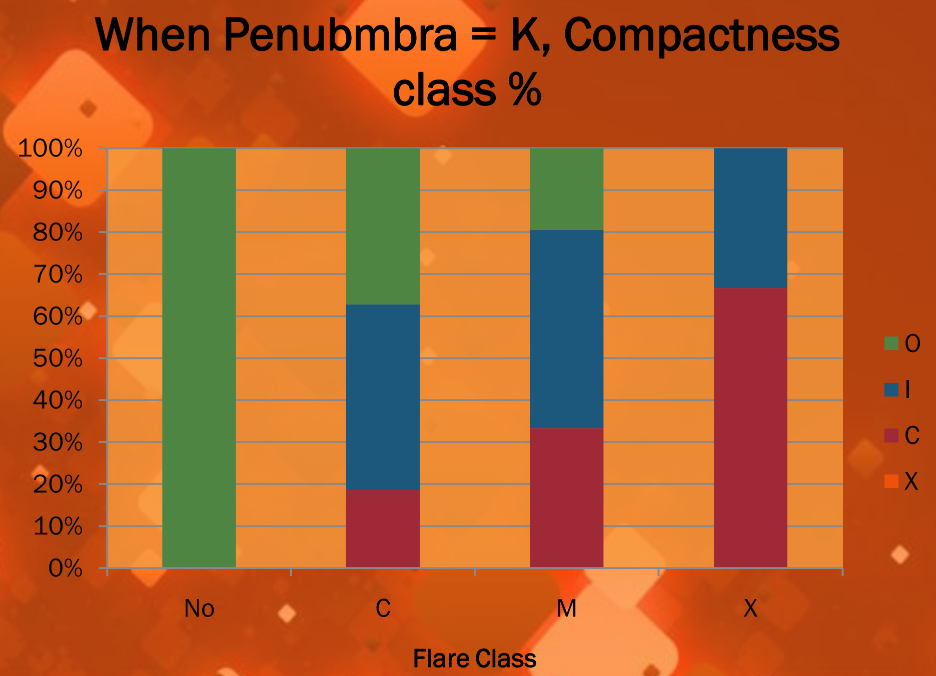
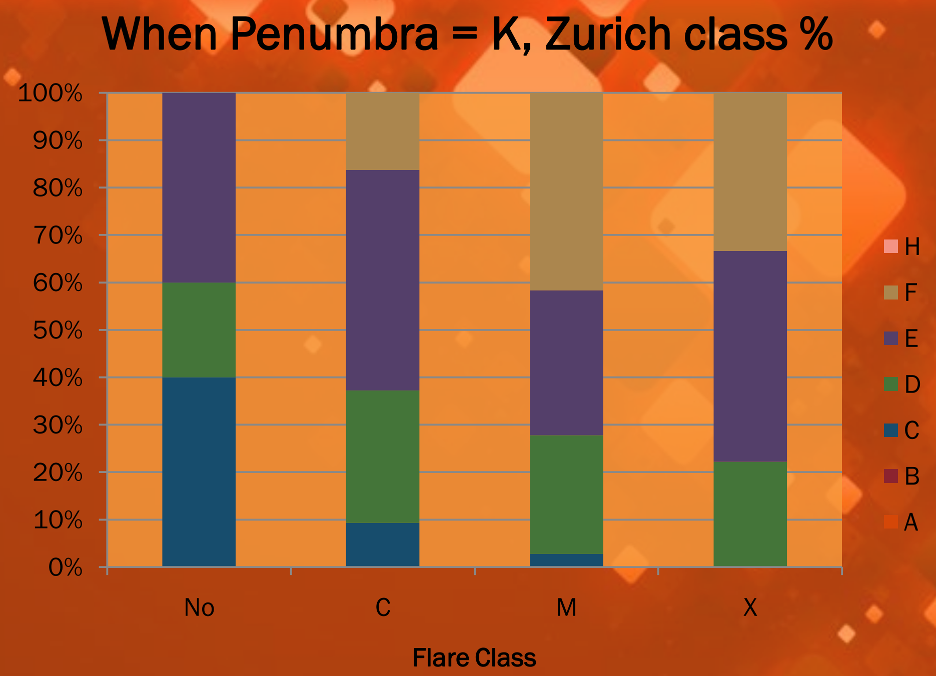
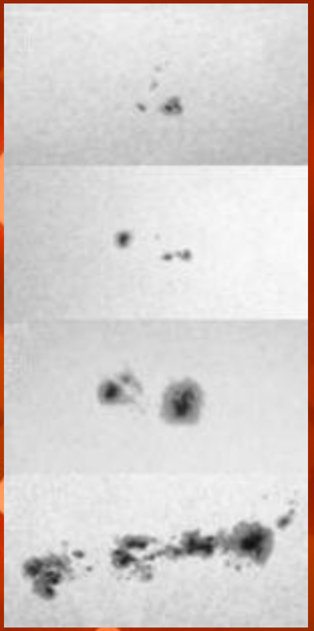
D
C
B
A

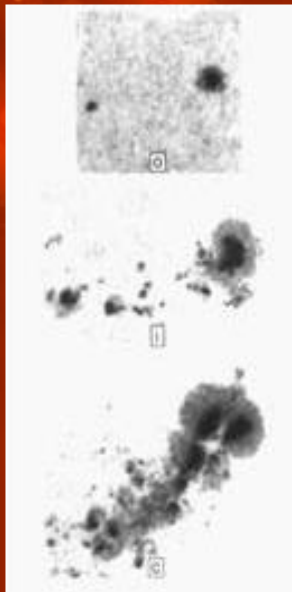




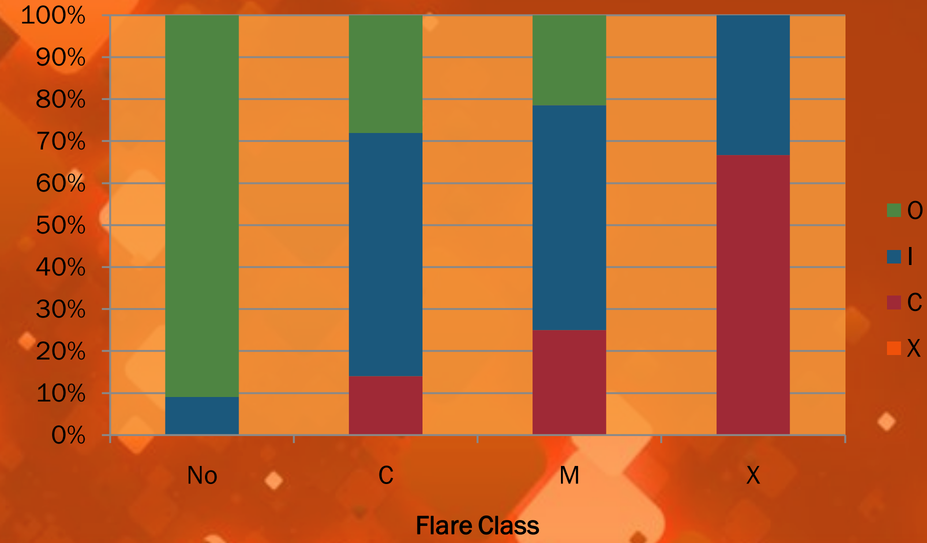

When Penubmbra = K, Compactness class %
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
No
C
M
X
Flare Class
O
I
C
X


When Penumbra = K, Zurich class %
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
No
C
M
X
Flare Class
H
F
E
D
C
B
A

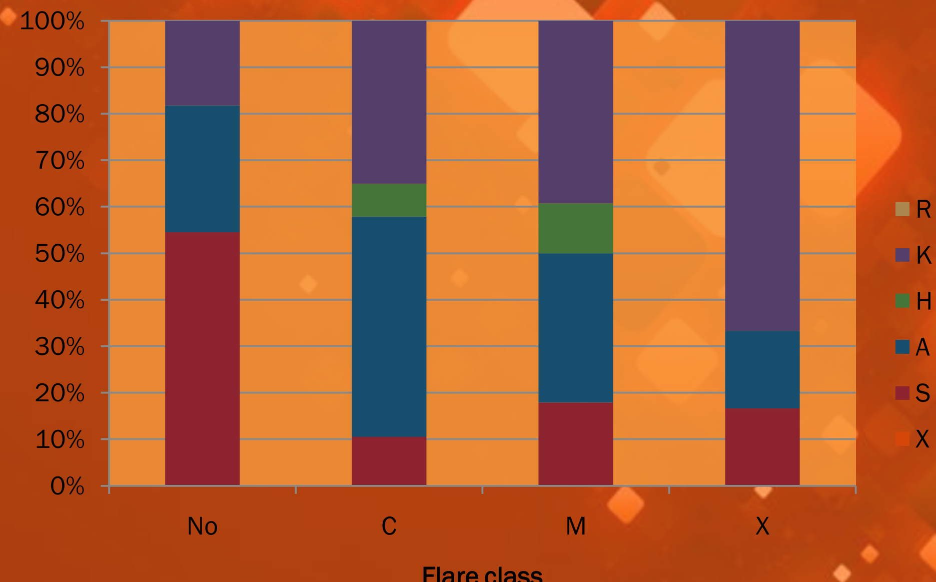


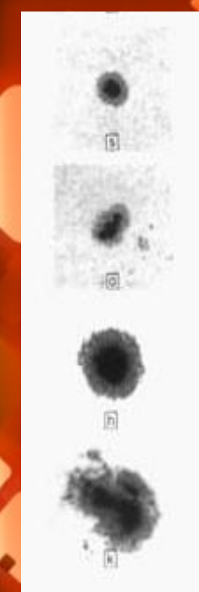


When Zurich = E, Compactness class%



When Zurich = E, Penubra class%





Conclusion

- The more compact the sunspot group is, the higher the probability of producing an x-class flare.
- Asymmetric penumbra sunspots are more likely to flare in the x-class than symmetric penumbra sunspots.
- Elongated bipolar sunspot groups with penumbra at both ends are more likely to flare in the x-class than single spots, those without penumbra, and uni-polar sunspots.
- Increasing compactness and complexity of a sunspot increases NHGV
- Work-in-progress.

Sources

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