A sunspot's tale

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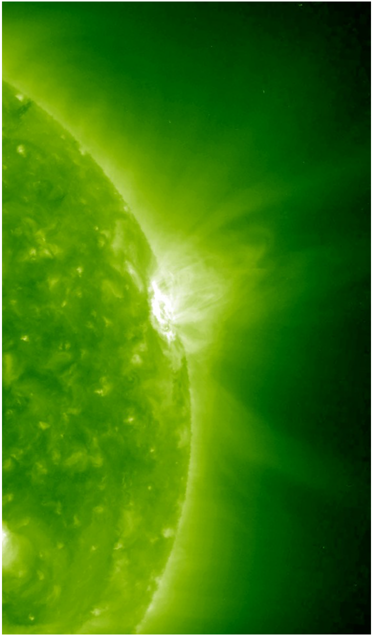
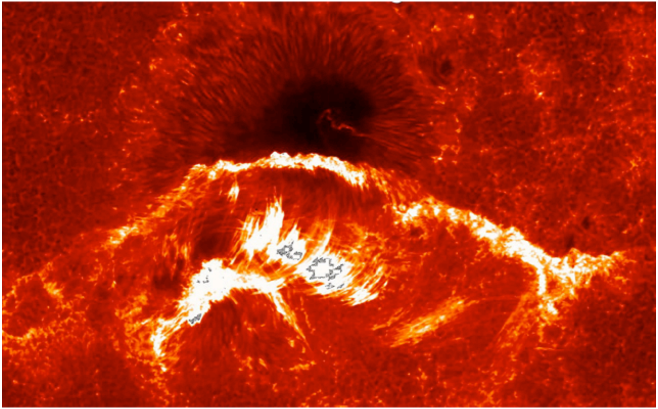


AR 11029 at 195Å (sohowww.nascom.nasa.gov)

Overview

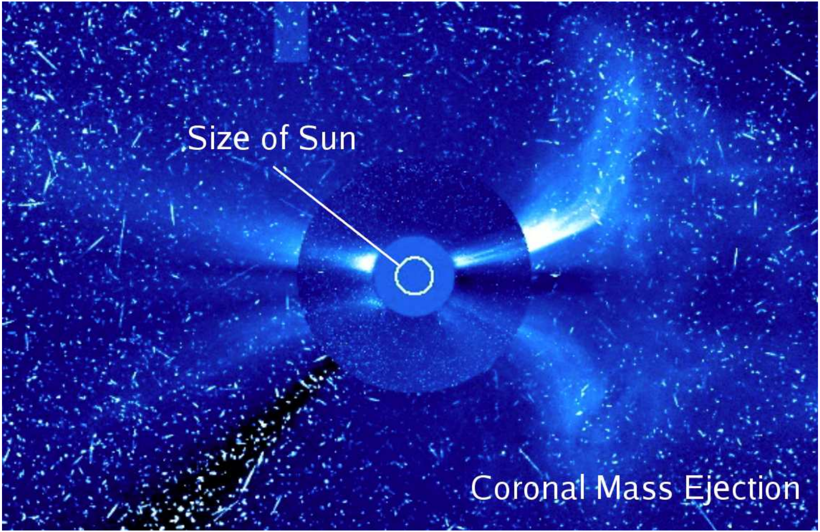
Background – Sunspots and solar flares

- Sunspots: regions with strong surface magnetic fields
- Sunspot magnetic fields power “solar activity”:
  - solar flares – magnetic explosions in the atmosphere (corona)
  - Coronal Mass Ejections (CMEs) – expulsions of material
- A large solar flare caught in the act:



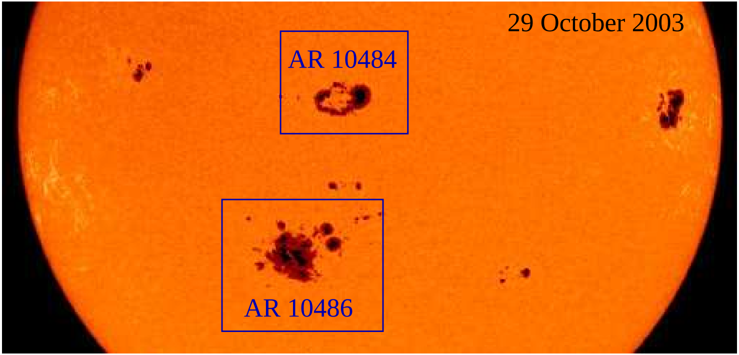
A flare and a sunspot: 12 Dec 2006 [Hinode/SOT]

- Coronal mass ejections
  - CMEs influence our local "space weather"
  - produce storms of energetic particles (Solar Proton Events)



A coronal mass ejection (CME) and a Solar Proton Event [SOHO/LASCO]

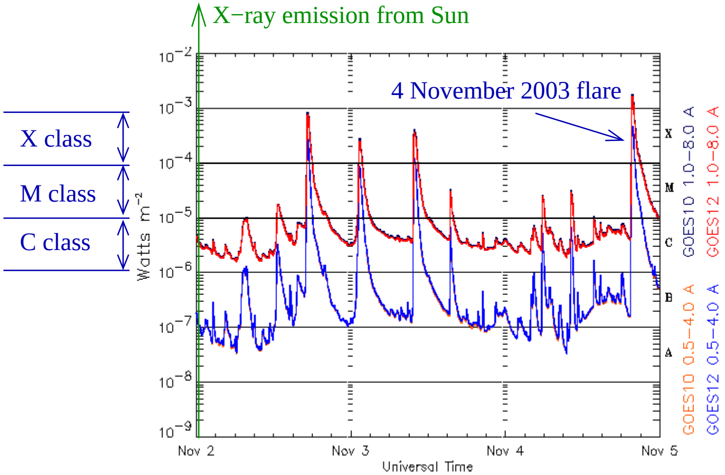
- Areas around sunspots are "active regions" (ARs)
  - assigned numbers by US NOAA
- Large regions may produce many flares in crossing the disk
  - e.g. ARs 10484 and 10486 in Oct-Nov 2003
  - AR 10486 produced the largest flare of the modern era[1]



ARs 10484 and 10486 produced a sequence of huge flares in October-November 2003 [MDI]

[1] For a good read see Stuart Clark 2007, "The Sun Kings," Princeton University Press

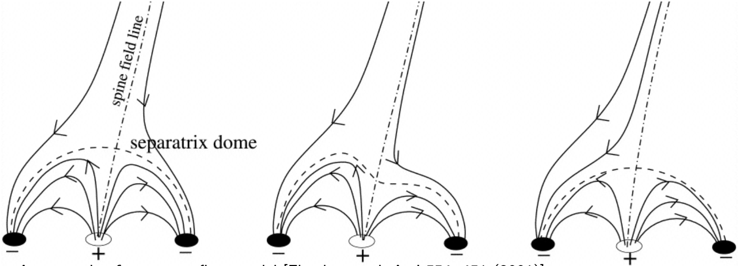
- Flares are classified by their peak GOES flux (1-8 Å X-rays)
  - GOES: Geostationary Observational Environmental Satellites
    - small flares are GOES C-class
    - medium are M-class and large are X-class



Plot of GOES data showing the largest flare of the modern era [NOAA]

The flare mechanism

- Flares involve release of magnetic energy via "reconnection"
  - reconnection involves a change of magnetic connectivity
- Details of the process are not well understood
  - theories often at the level of "cartoons"[2]



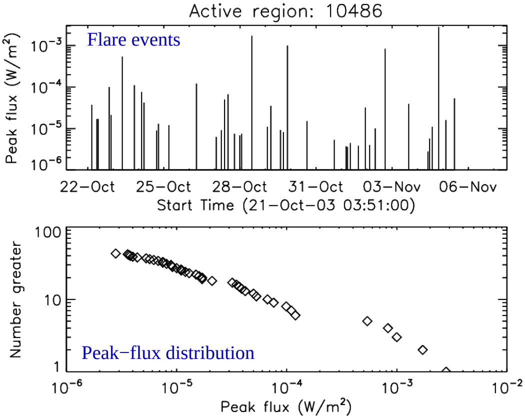
An example of a cartoon flare model [Fletcher et al. ApJ 554, 451 (2001)]

- There is great variety in flare observations
  - looking at the statistics of many flares may provide insight

[2] See e.g. Hugh Hudson's cartoon archive: `http://solarmuri.ssl.berkeley.edu/~hhudson/cartoons/`

Solar flare statistics

- Statistics of GOES flares in AR 10486
  - top panel: peak flux of events versus time
  - lower panel: peak-flux distribution



Flares in AR 10486 in Oct-Nov 2003 including the biggest flare of the modern era

Flare size distribution

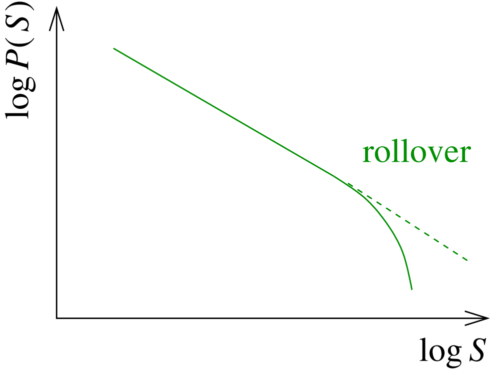
- Size S: a measure of the magnitude
  - e.g. peak GOES flux
  - a proxy for energy
- Flares obey a "power-law" size distribution: (e.g. Akabane 1956)

$$P(S) = AS^{-\gamma} \tag{1}$$

  - $P(S)$ is number of flares per unit S
  - γ is the "power-law index" ($\gamma \approx 1.5$–2)
  - a power law is a straight line on a log-log plot
- The power law appears universal
  - same index at different times and in different active regions
- Power laws are surprisingly common (e.g. Newman 2005)
  - sizes of cities, earthquake energies, wealth of individuals, etc.

Flare size distribution

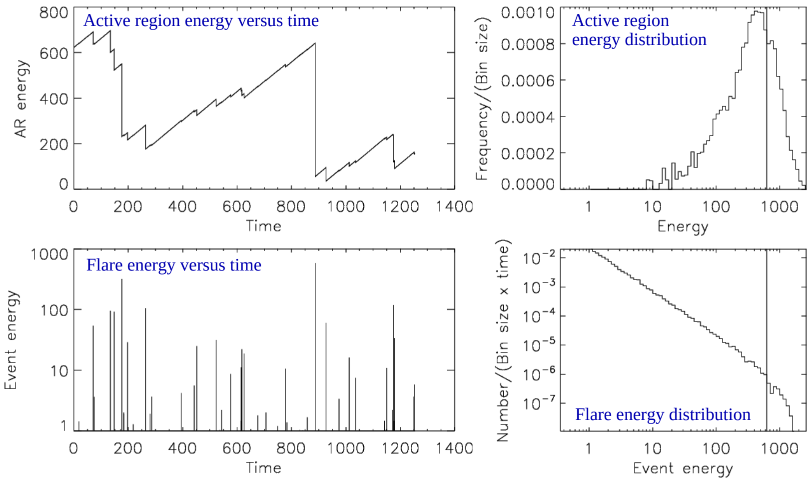
- An upper limit to Eq. (1) must exist
  - there must be a "rollover" (departure from the power law)
    - representing a limit on the energy available for flaring
    - the magnetic field only has so much energy available
  - but it has proven very hard to identify this "size limit"
    - not identified for individual active regions to date
  - evidence based on many small regions (e.g. Kucera et al. 1997)



Models for flare statistics

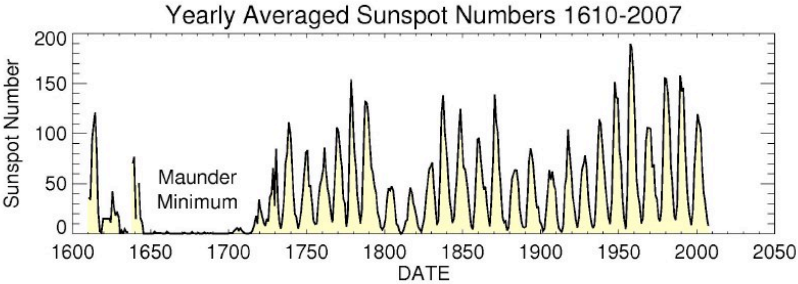
- Popular model: “avalanche model” (Lu & Hamilton 1991)
  - “cellular automaton” (grid) in a “self-organised critical state”
    - field on a grid close to instability everywhere
    - disturb grid by continually adding random elements
  - flare involves avalanche of local energy release events
    - a local event redistributes field
    - causes neighbouring sites to also release energy
  - model produces a power-law size distribution
    - departure at very large sizes due to finite grid
- Energy balance models (Rosner & Vaiana 1978)
  - accounting of energy input and loss in an active region
- General stochastic model (Wheatland 2008; 2009)
  - model produces a power-law energy distribution
    - with a rollover at large energy

- Example of stochastic modelling



Solar cycles

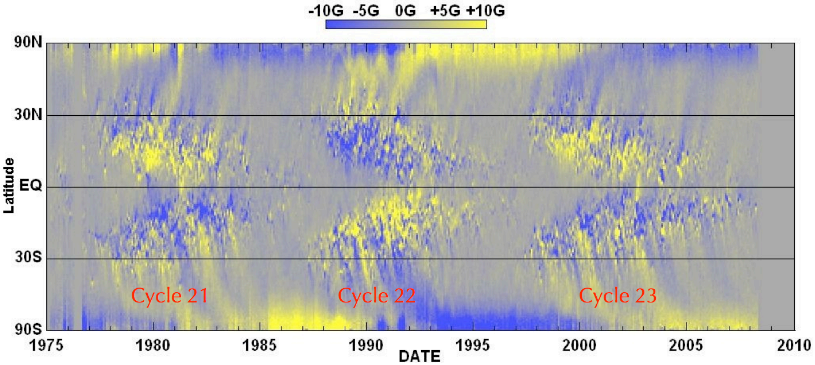
- The average sunspot number varies with an 11-year cycle
  - but the variations are not very regular
  - the maximum number over a cycle varies a lot
  - recent cycles are numbered: the last was cycle 23
  - and the next is cycle 24...
- There is much more solar activity at a “solar maximum”



The sunspot record since the invention of the telescope [http://science.nasa.gov/]

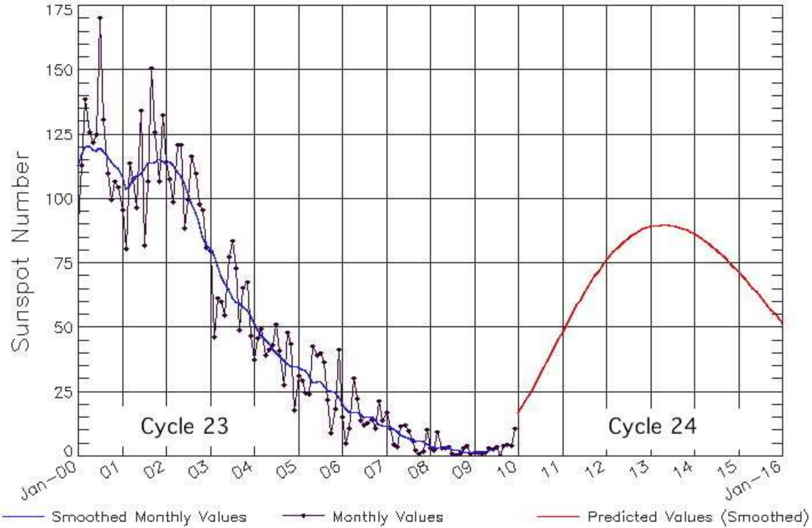
Hale cycle

- Patterns in the surface magnetic field repeat every 22 years
  - "polarity": sign of magnetic field
  - N is positive (pointing out), S is negative (in)
- Early spots of a new cycle appear at high latitude...
  - ...with a reversed polarity wrt rotation direction
  - hence can identify "new cycle spots"



Azimuthal averages of the surface field [NASA/MSFC/NSSTC/Hathaway 2008]

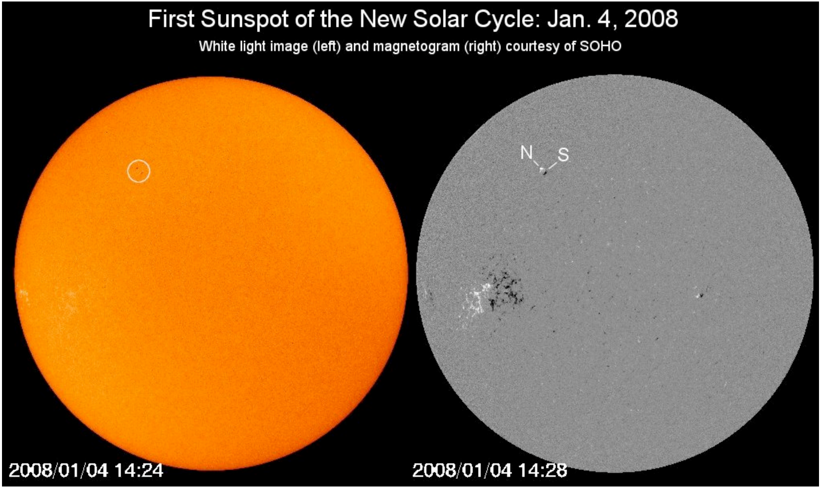
- We are currently at solar minimum
  - the red curve is a prediction



Recent sunspot numbers [http://www.swpc.noaa.gov/SolarCycle/]

The first new cycle spot – Jan 2008

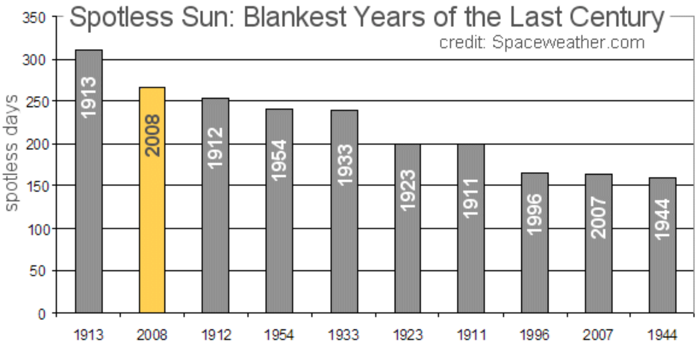
- A small northern hemisphere region with leading S polarity
  - signature of a cycle 24 region



There have been some new cycle spots [http://science.nasa.gov]

Has the Sun lost its spots?

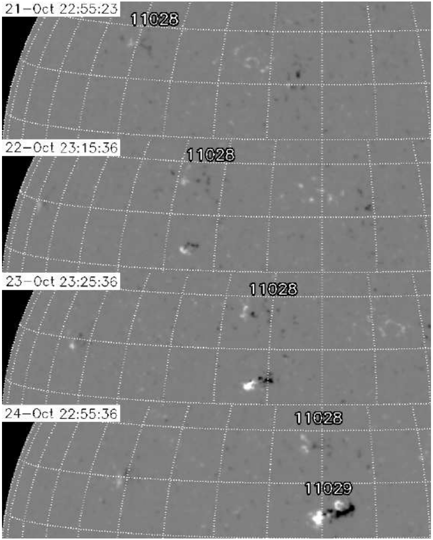
- The new cycle (24) has taken a while to start
  - relatively few new cycle spots
  - 2008 had 266 “spotless” days (73%)
    - need to look back to 1913 for a blanker year (85%)
  - 2009 had 260 spotless days (71%)
- This year has been more promising
  - only two spotless days so far (7%)



The recent deep minimum [http://science.nasa.gov]

A sunspot's tale – Active region 11029

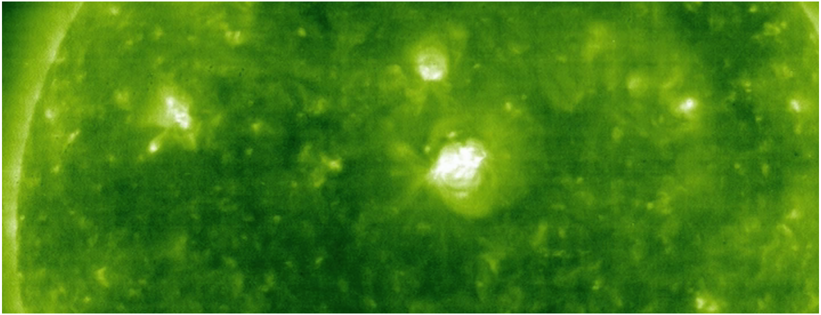
- A new cycle region emerged on the disk on 21-22 Oct 2009



Line-of-sight magnetic field 21-24 Oct 2009 (`www.solarmonitor.org`)

Development

- Sunspots developed and the region was labelled 11029
- The region grew in size and complexity
  - but remained relatively small ($< 400\,\mu$-hemispheres)
  - an extreme-UV movie shows the development

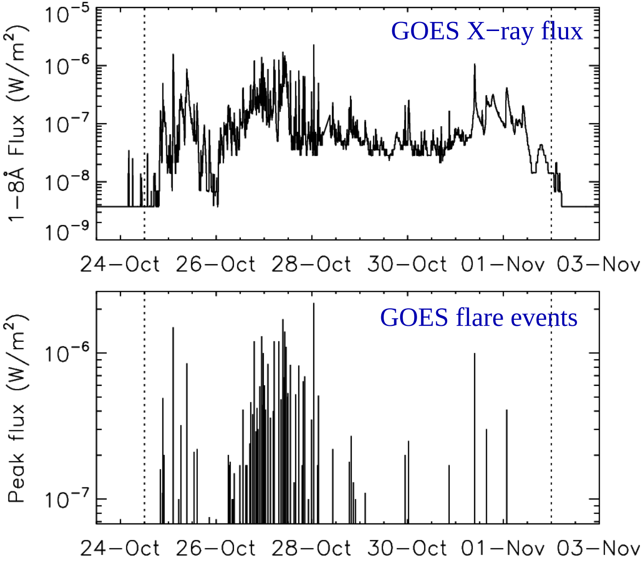


The development of active region 11029 (`sohowww.nascom.nasa.gov`)

Flaring

- AR 11029 became *highly* flare-productive
  - US Space Weather Prediction Center: 73 GOES events
  - all small (one A-class, 60 B-class, and 11 C-class)
  - no medium or large flares (M-class or X-class)
- Flares observed in isolation due to the minimum
  - unique opportunity to examine flare statistics
  - chance to catch all flares!
- Basic question:
  - is there a departure from the power-law size distribution?

X-ray emission and flare events

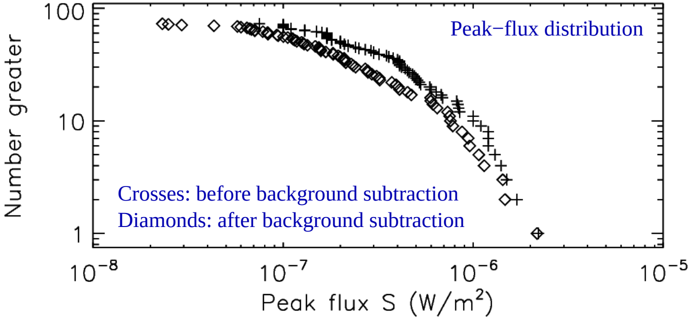


Time history of X-rays from AR 11029, and the 73 flare events for the region (US SWPC/NOAA)

Analysis of peak-flux distribution

Background subtraction

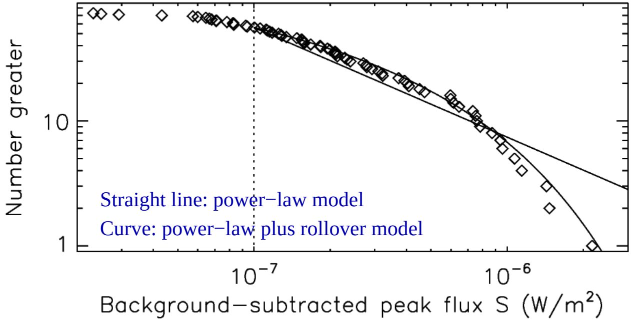
- The GOES peak fluxes are not background subtracted
  - the background varies by a factor of ten (see GOES plot)
  - important to background subtract for small events
- The size distribution for the events changes substantially
  - it appears to show departure from a simple power law



Background subtraction of the peak fluxes of events

Quantitative analysis of peak-flux distribution

- Two models compared against the data D:
  - a power law and and power law plus exponential rollover
- Bayesian parameter estimation applied
  - approach to probability based on Bayes's theorem (e.g. Jaynes 2003)
- Advantages of the Bayesian approach:
  - estimation of parameters does not involve binning the data



Peak-flux distribution and the power-law and power-law plus rollover models

- Bayesian model comparison also applied
  - "global odds ratio" is

$$r_{\mathrm{plr/pl}}(D) \approx 220$$

    - relative probability of the models given the data
    - assuming both models a priori equally likely
  - power law plus rollover is 200× more probable
  - i.e. this model is *strongly* favoured by the data

Interpretation

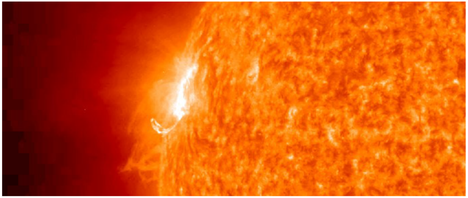
- Size distribution implies the existence of a "size limit"
  - a largest flare this region is capable of producing
    - AR 11029 is small and so has a limited amount of energy
    - it is highly flare productive and hence reveals its limit
- This has never before been seen for an active region
  - advantage of observing a small region in isolation

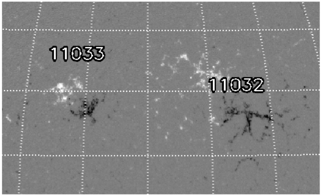
Journal article

- Just published (online):
  - M.S. Wheatland, Astrophysical J. 710 1324-1334 (20 Feb 2010)

Exit, pursued by a bear

- AR 11029 rotated off the disk on 1-2 Nov
  - it was still flaring (although less vigorously)
- The region returned to the disk on 14 Nov
  - and was relabelled AR 11032
- The region had dispersed - it was dying!
  - a diffuse β region: not flare-productive





The return of our active region... as AR 11032

Summary

- Sunspots power solar activity e.g. flares and CMEs
  - flares are poorly understood
- Flare statistics provide some insight
  - flare frequency-size distribution is a power law
- Activity varies with an 11/22-year cycle
  - we have been at solar minimum
  - the Sun lost its spots
- Active region 11029 caused a stir in late Oct 2009
  - produced many small flares
  - was seen in isolation due to minimum
  - size distribution shows departure from a power law
    - interpreted in terms of a size-limit for this small region

- List of solar sites including pictures and movies: http://sydney.edu.au/science/physics/~wheat/[3]

[3] Easier: search for Mike Wheatland on google.