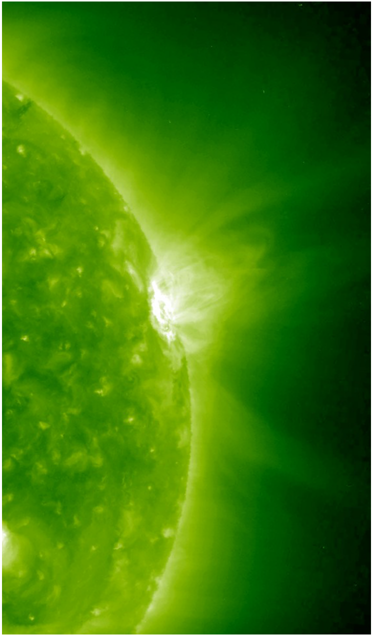
A sunspot's tale

M. S. Wheatland

School of Physics
Sydney Institute for Astrophysics
The University of Sydney

School Colloquium
30 November 2009

The University of Sydney

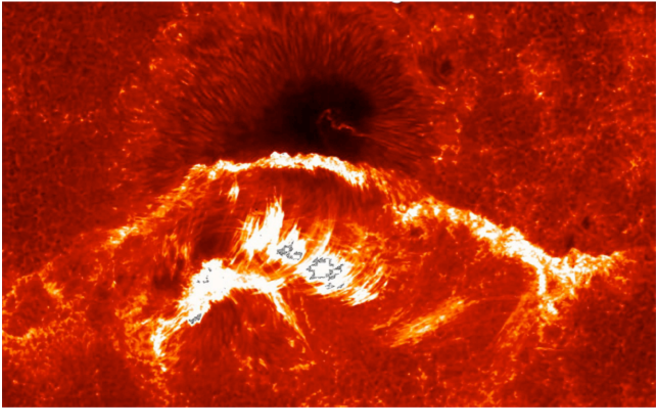


AR 11029 at 195Å (sohowww.nascom.nasa.gov)

Overview

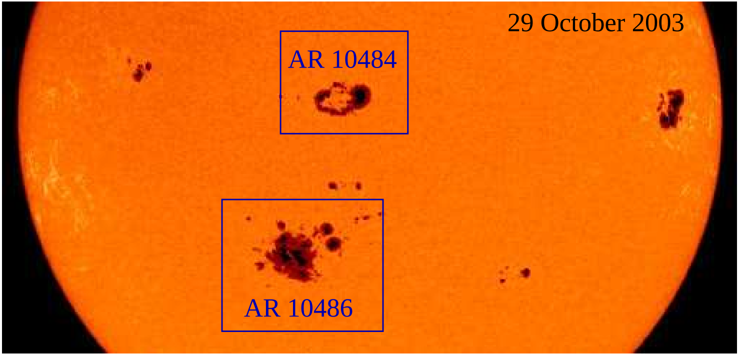
Background – Sunspots and solar flares

- Sunspots: regions with kG 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 flare and a sunspot: AR 10930, 12 Dec 2006 [Hinode/SOT]

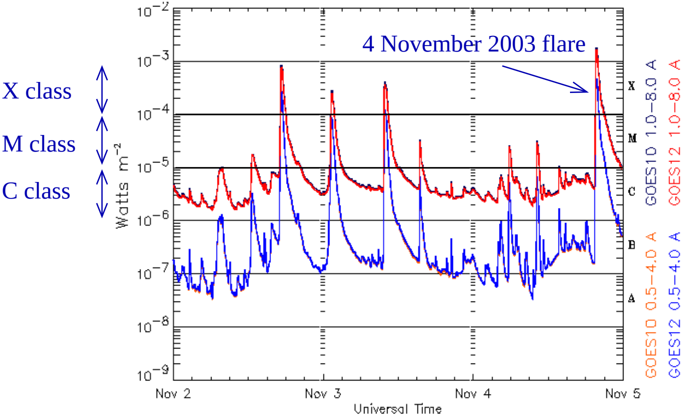
- Areas around sunspots are "active regions" (ARs)
  - assigned numbers by US NOAA
- Large regions may produce many flares in crossing the disk
  - e.g. ARs 10484 and 10486 in Oct-Nov 2003
  - AR 10486 produced the largest flare of the modern era[1]



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

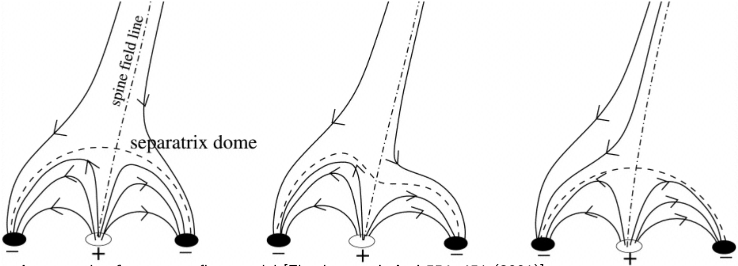
- Flares are classified by their peak GOES flux (1-8 Å X-rays)
  - GOES: Geostationary Observational Environmental Satellites
    - small flares are GOES C-class (peak flux $> 10^{-6}\,\mathrm{W\,m^{-2}}$)
    - medium are M-class ($> 10^{-5}\,\mathrm{W\,m^{-2}}$)
    - large are X-class ($> 10^{-4}\,\mathrm{W\,m^{-2}}$)



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

Frequency-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)

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

  - $f(S)$ is number of flares per unit time, per unit S
  - γ is the "power-law index" ($\gamma \approx 1.5$–2)
- The power law appears universal
  - same index at different times and in different active regions
- An upper limit to Eq. (1) must exist
  - there must be a "rollover" or departure from the power law
    - there is a finite amount of energy available for flaring
  - however it has proven very hard to identify this "size limit"
  - some evidence based on *many* small regions (e.g. Kucera et al. 1997)

Waiting-time distribution

- Occurrence of flares in time appears random
- Characterise by looking at "waiting times" τ
  - the times between flares
  - construct waiting-time distribution $P(\tau)$
- For random flaring at a constant mean rate λ_1:

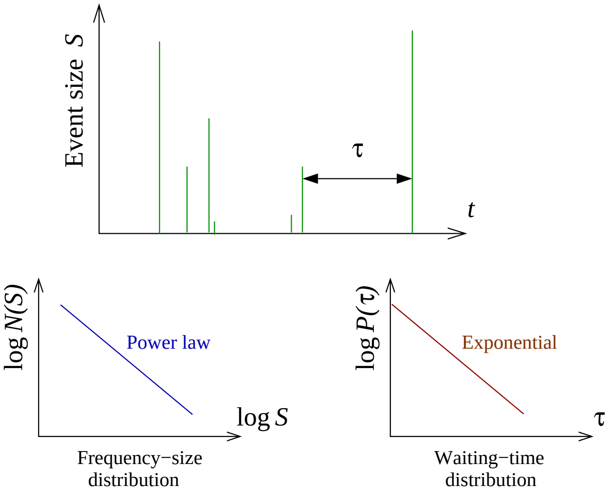
$$P(\tau) = \lambda_1 \exp(-\lambda_1 \tau) \tag{2}$$

  - λ_1 is the mean rate of events above size S_1
  - the distribution is exponential
  - this is a "Poisson process"
- There is a simple relationship between λ_1 and A in Eq. (1):

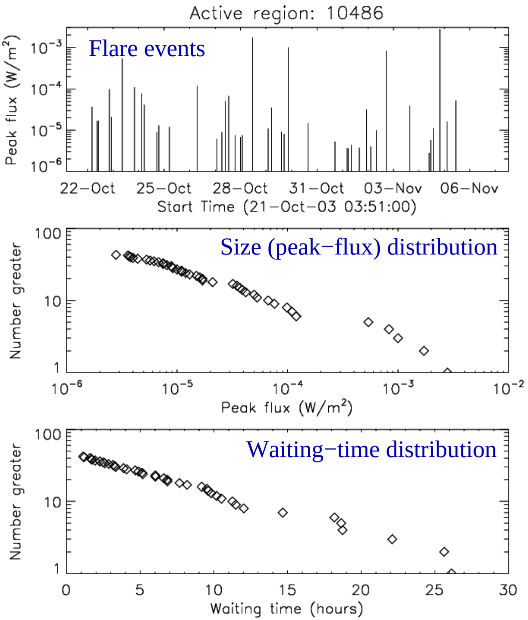
$$A = \lambda_1(\gamma - 1)S_1^{\gamma-1} \tag{3}$$

- If the rate is time-varying $P(\tau)$ is more complex
  - piecewise-constant rate: sum of exponentials

- The frequency-size and waiting-time distributions
  - a power law is a straight line on a log-log plot
  - an exponential is a straight line on a log-linear plot



- Statistics of GOES flares in AR 10486



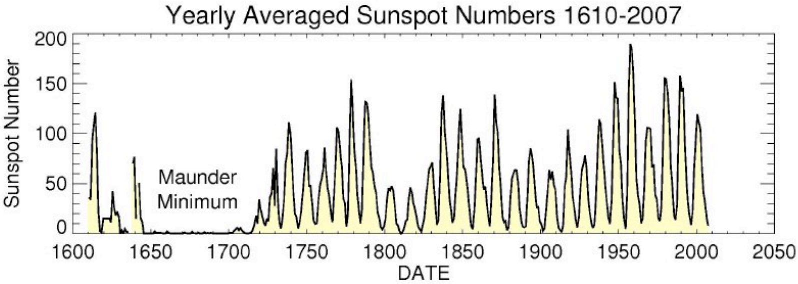
Flares in AR 10486 in Oct-Nov 2003 including the biggest flare of the modern era

Models for flare statistics

- The avalanche model is popular (Lu & Hamilton 1991)
  - cellular automaton in a "self-organised critical state"
  - flare consists of an avalanche of local energy release events
  - produces a power-law frequency-size distribution
  - Poisson occurrence in time (exponential waiting times)
  - but the model has no physical basis
- Energy balance models (Rosner & Vaiana 1978)
  - accounting of energy input and loss by an active region
- General stochastic model (Wheatland & Glukhov 1998; Wheatland 2008; 2009)
  - power-law frequency-size distribution
  - exponential waiting-time distribution (in steady state)
    - provided mean active region energy is $\gg$ flare energies
  - can also model time dependence

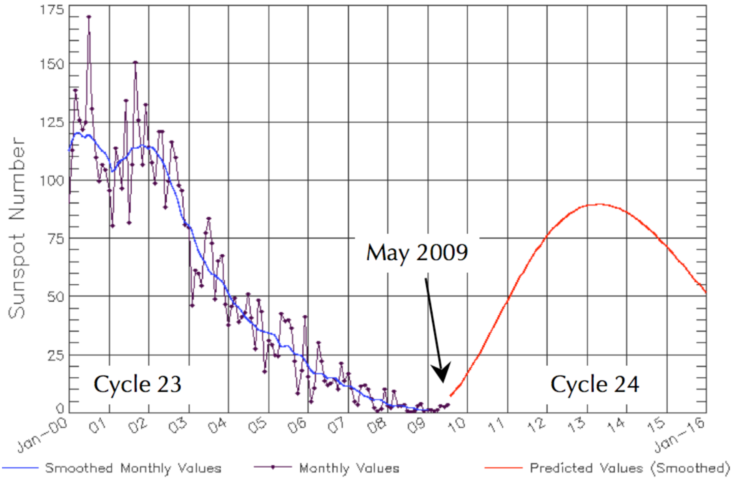
The solar cycle

- 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/]

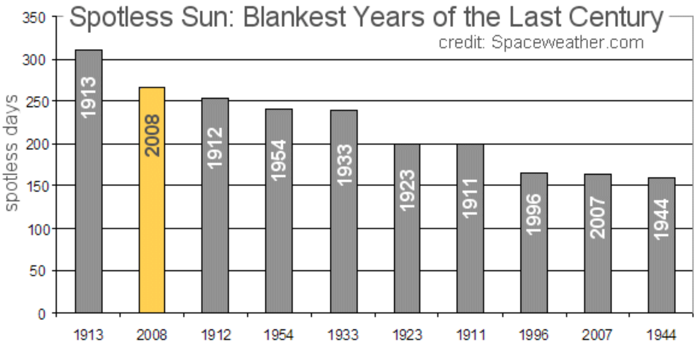
- We are currently at solar minimum
  - the red curve is a prediction (ask Richard Thompson!)



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

A deep minimum

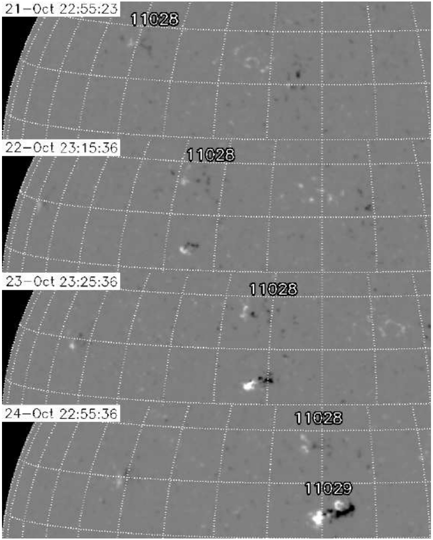
- The new cycle (24) is taking a long time to start
  - there have been very few sunspots
  - the last X-class flare was in December 2006
- We are experiencing a "century-level minimum"
  - 2008 had 266 "spotless" days (73%)
  - you need to look back to 1913 to find a blanker year (85%)
  - 2009 has had 249 spotless days already (75%)



A deep minimum [http://science.nasa.gov]

A sunspot's tale – Active region 11029

- Active region 11029 emerged on the disk on 21-22 Oct 2009



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

Development

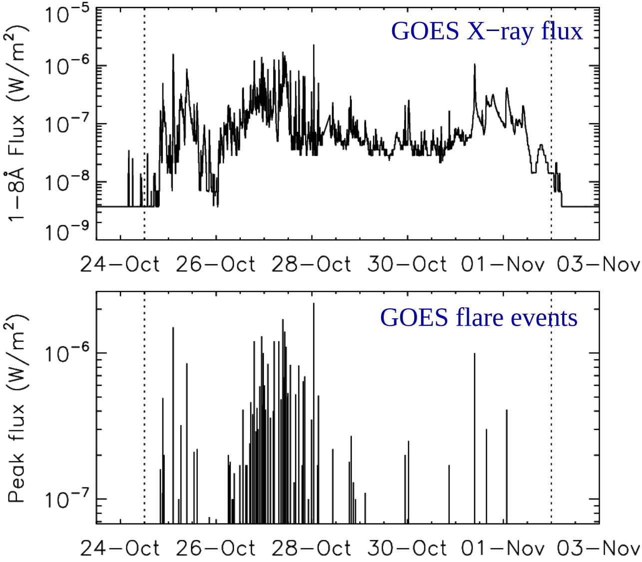
- The region grew in size and complexity
  - but remained relatively small ($< 400\,\mu$-hemispheres)
- Magnetic complexity characterised by "Mount Wilson" class
  - initially the region was β (simple bipolar)
  - developed into β–γ on 26 Oct (more complex)
- AR 11029 is a "new-cycle region"
  - identified by polarity (sign) of the magnetic field configuration
  - hemispheric polarity reverses with each cycle (Hale's law)
  - N-hemisphere cycle 24 spots have leading negative polarity
- 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)

Table: Daily behavior of solar active region AR 11029.

Day	Classification	Sunspot area (μhs)	GOES events	Comments
21–22 Oct	–	–	0	Emergence
24 Oct	β	50	4	Sunspot formation
25 Oct	β	120	7	
26 Oct	β–γ	130	24	
27 Oct	β–γ	190	23	
28 Oct	β–γ	260	8	
29 Oct	β–γ	340	2	
30 Oct	β	380	2	
31 Oct	β	320	2	
1 Nov	–	–	1	Rotated off disk

- Flares observed in isolation due to the minimum
  - unique opportunity to examine flare statistics
  - chance to catch all flares!
- Basic questions:
  - is there a departure from the power-law size distribution?
  - what is the waiting-time distribution?

X-ray emission and flare events

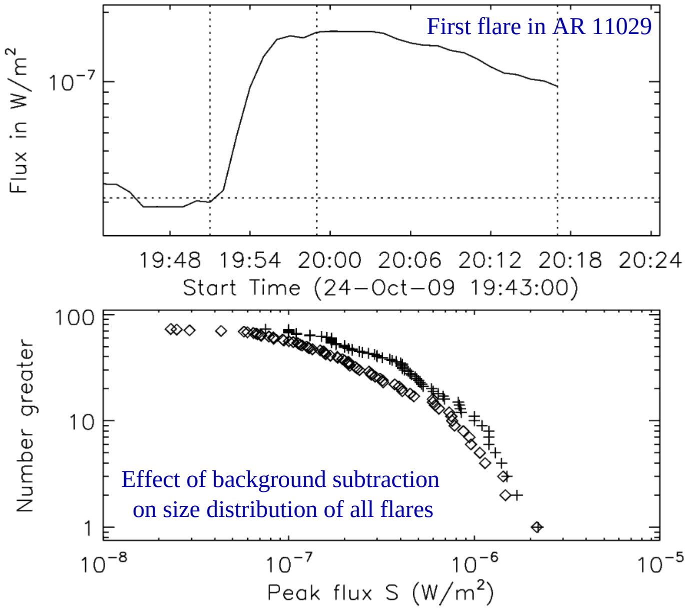


Time history of X-rays from AR 11029, and the 73 flare events for the region (US SWPC/NOAA)

Analysis

Background subtraction

- The GOES peak fluxes are not background subtracted
  - background variation a factor of ten (see GOES plot)
  - important to background subtract for small events
- For each event:
  - rise time t_r (peak time minus start time) calculated
  - average of flux for interval t_r before start time calculated
    - this is taken as background estimate
  - background-subtracted peak fluxes calculated
- 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 size distribution

- Two models compared against data D:
  - power law and power law plus exponential rollover

$$P_{\mathrm{pl}}(S) = BS^{-\gamma} \quad \text{and} \quad P_{\mathrm{plr}}(S) = CS^{-\gamma}\mathrm{e}^{-S/\sigma} \tag{4}$$

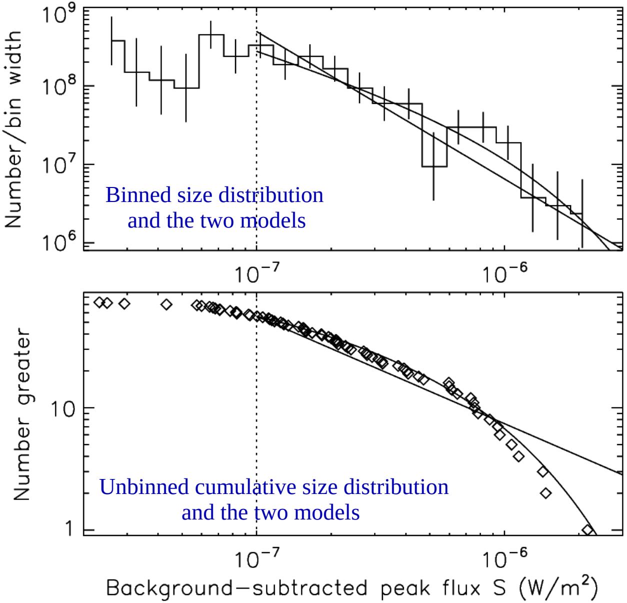
  - models assumed above $S_1 = 10^{-7}\,\mathrm{W\,m^{-2}}$
- Bayesian parameter estimation/model comparison (e.g. Jaynes 2003)
  - no binning of data
  - direct comparison of probabilities of models given data
    - taking into account all possible parameter values
- Results:
  - index for power-law model is $\gamma_{\mathrm{pl}} = 1.88 \pm 0.12$
  - parameters for power-law plus rollover model are

$$\gamma_{\mathrm{plr}} = 0.99 \pm 0.34 \qquad \sigma = 9.8 \pm 5.3 \times 10^{-7}\,\mathrm{W\,m^{-2}}$$

  - model comparison: odds ratio is

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

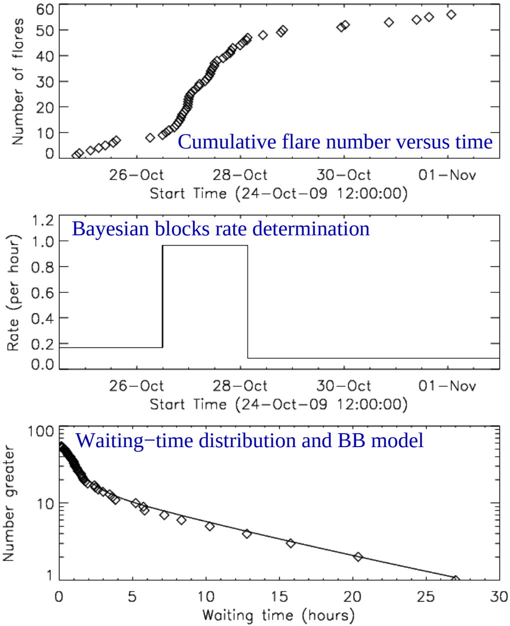
    - power-law with a rollover *strongly* favoured by data



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

Quantitative analysis of waiting-time distribution

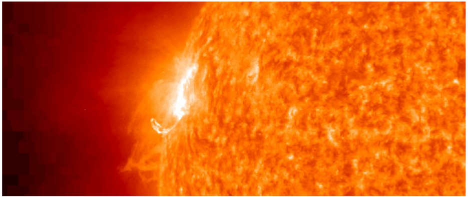
- Bayesian rate determination: Bayesian Blocks (Scargle 1998)
  - iterative Bayesian routine
  - determines a piece-wise constant Poisson model
  - defines a model waiting-time distribution
- Results:
  - Bayesian blocks decides on a three-rate model
    - interval of high rate (26 Oct and 27 Oct)
    - two intervals of comparably low rate
  - model waiting-time distribution essentially bi-exponential
    - because the two low rates are similar in value
  - model reproduces observed waiting-time distribution

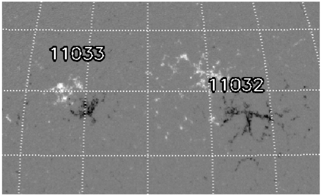


Analysis of the rate of flaring and of the waiting-time distribution

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

Conclusions

- Size distribution implies the existence of a "size limit"
  - a largest flare the region is capable of producing
  - this has never before been seen for an active region
    - advantage of observing a small region in isolation
- Waiting-time distribution reflects rate variation
  - occurrence in time appears random
  - rate very high for a short interval
    - coinciding with transition to Mt Wilson β–γ class

Summary

- Sunspots power solar activity e.g. flares
  - flares are poorly understood
- Flare statistics provide some insight
  - flare frequency-size distribution is a power law
  - flare occurrence in time appears random
    - characterised by waiting-time distribution
- Currently we are in a deep solar minimum
- Active region 11029 created 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 as size-limit for a small region
  - waiting-time distribution reveals clear rate variation
- List of solar sites including pictures and movies:
  www.physics.usyd.edu.au/~wheat/solar_links.html