Solar Flares and CMEs

Solar Physics 1
What is a solar flare?
What is a CME?

A solar flare is a sudden eruption of energetic charged particles from the Sun’s corona.

A coronal mass ejection (CME) is, by definition, an ejection of mass from the Sun’s corona.
The Sun

• What is the Sun made up of?
• What is the convection zone? What’s important about it?
• What is the photosphere?
• What are sunspots?
Cause of solar flares & CMEs

- Solar flares mostly occur around sunspots
- Magnetic reconnection
- Both CMEs and solar flares are caused by the same process
To put things into perspective...

• Solar flares are extremely energetic – they can have up to $10^{30}$ joules of energy. That’s equivalent to 100 trillion one-megaton nuclear weapons exploding at once!

• CMEs are huge; a large CME can eject a billion tonnes of matter outwards near the speed of light!
Solar flares & CMEs

• Well solar flares and CMEs are usually found to occur at the same time, but can they both occur without the other?
Using information from the NASA database we found that:

- There were two solar flares for every CME.
- Typically there would be a solar flare four hours before the CME.
- There would not always be a CME after a solar flare.
- So we can postulate that for a CME to occur a solar flare must occur before in the vicinity of a few hours beforehand.
Assumptions/Limitations

- Solar cycles are not consistent
- Limited data available
- Values used are averaged
Initial Data (Feb/Mar)
Distribution of Solar Flare Intensities

• Count the total time of flares within intervals of different intensity (each one twice as large as the previous):
  – $1\times10^{-6}$ to $2\times10^{-6}$
  – $2\times10^{-6}$ to $4\times10^{-6}$
  – $4\times10^{-6}$ to $8\times10^{-6}$ and so on...

• Due to the size of the data, intervals of the same size cannot be used.
Exponential?

- The previous graph looked “exponential”.
- Thus, plotting $\ln(y)$ instead of $y$ we get...
New Graph

$y = -0.9578x + 10.115$

$R^2 = 0.9885$
Linear Graph!

- $R^2$ is the coefficient of determination, which is a value from 0 to 1.
- 0 means the graph is completely random, 1 means the graph is perfectly linear.
- The graph had $R^2=0.99$, which means that it approximates the real data very well, and future outcomes can be well predicted by the model.
Probability Density Function

- Since the graph of ln(y) against ln(x) is linear...
- The probability density function is a polynomial of the form $y=ax^b$.
- Solving for the constants (using the combined Feb/Mar data) we get:
  \[ y = (1.281 \times 10^{-9})x^{-2.382} \]
  \[ \text{where } x \text{ is the intensity of the solar flare in } \text{Wm}^{-2}. \]
Predicting Probabilities of Solar Flares

- In order to estimate the probability or proportion of time with a certain range of solar flare intensity, we integrate the previous equation on that range.

- For example, the proportion of time with solar flare intensities in the M class \((10^{-5} \text{ to } 10^{-4})\) is approximately 0.72%, while that of the X class \((10^{-4} \text{ to } 10^{-3})\) is approximately 0.03%. 
Limitations

• Because the graphs were made using data of solar flares of intensity between $10^{-6}$ and $\sim 3 \times 10^{-4}$, we cannot safely predict solar flares outside this range (roughly C to X class).

• This is because the graphs can only be interpolated but not extrapolated.
Limitations

• Due to the solar cycle, the X-ray data can actually fluctuate significantly across the months or years.

• Thus our model is mainly good for months at the same stage of the solar cycle (compared to Feb/Mar 2011).

• The greater the difference in the solar cycle, the greater the discrepancy in our predictions.
Limitations

- In fact, if we studied the graphs of Feb and Mar separately, we already get significantly different graphs.
Significance

• Both graphs had $R^2=0.97$, which suggests that they are highly linear as well, and thus the probability density function would still be of the form $y=ax^b$.

• However, the constants vary significantly.

• If we want to accurately predict solar flares, we need to base our estimations on data from a similar stage of the solar cycle.
Waiting Time between Solar Flares
Why Waiting Time?

• Since we couldn’t see any obvious trends in the data, analysing waiting time collectively could tell us more about solar flare occurrence.

• We conjectured that solar flares may occur according to a Poisson distribution.
  – If waiting time obeys exponential distribution, then process is Poissonian.
Waiting Time between Solar Flares
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Threshold
Waiting Time between Solar Flares

Threshold
Waiting Time between Solar Flares
Waiting Time between Solar Flares
Initial Data (Feb/Mar)
Waiting Time Graphs

Frequency against Waiting Time
Waiting Time Graphs

In of Frequency against Waiting Time

\[ y = -0.1117x + 3.7465 \]

\[ R^2 = 0.9308 \]
Limitations

• Very small sample size (only 100+ waiting times to compare).
  – Frequency graph very prone to random error.
Implications

• If the process is truly Poissonian, then it is actually quite random and impossible to predict accurately.

• However, being able to determine the exact parameters of the distribution would enable us to better understand and ‘predict’ solar flare activity.
  - For example, from the data we can predict that the solar flare intensity may cross the $5 \times 10^7 \text{ W/m}^2$ threshold once every 72 minutes on average.
Implications of solar flares

• Solar flares release high energy particles ($10^{17}$J to $10^{25}$J of energy) which are potentially dangerous to life on earth.

• X-rays from flares are stopped by the atmosphere above the Earth. The small number that do get to reach the Earth does not significantly increase the level of radiation we receive each day.

• They also combine with energetic UV radiation and heat the Earth atmosphere's which causes it to expand.
Implications of CMEs

- CME’s are more likely to occur during the active phase of the Sun 11-year cycle; last maximum in solar activity was in 2000 next CME is expected to be in 2011 or 2012.
- When a CME reaches the Earth it disturbs the Earth’s magnetosphere.
- Damage to Earth’s orbiting satellites. The satellite becomes charged during a geomagnetic storm and a component is damaged by the high current that discharges into the satellite.
- Loss of radio communications.
- Loss of electrical power.
  - (e.g. Quebec in 1989)
Summary

- Damage to satellites caused by CME’s can be very expensive and disruptive.
- CME’s cause more disruption because of put heavy dependence on technical systems which are affected by high currents in the Earth’s magnetosphere.