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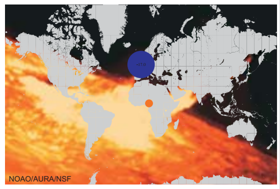
An estimation of the Carrington flare magnitude from solar flare effects (sfe) in the geomagnetic records



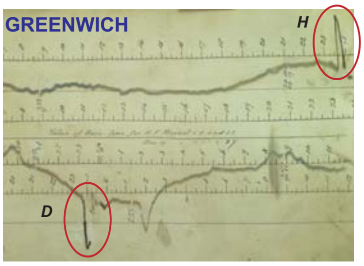
Ellen Clarke[1] (ecla@bgs.ac.uk), Craig Rodger[2], Mark Clilverd[3], Thomas Humphries[1], Orsolya Baillie[1], and Alan Thomson[1]
1 British Geological Survey, 2 University of Otago, 3 British Antarctic Survey

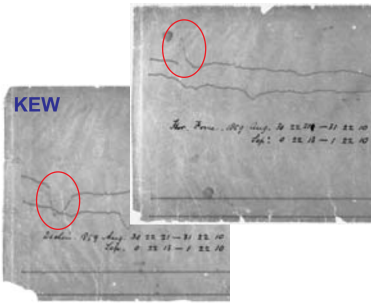
INTRODUCTION

The aim of this work was to derive a method of estimating the size of a solar flare from the related magnetic variation, or solar flare effect (*sfe*), observed at magnetic observatories. The particular goal was to re-assess the Carrington flare, which occurred at 11.15 UT on 1st September 1859. We review previous work to estimate the flare magnitude and re-examine observations of the *sfe* on the Kew and Greenwich (both London area) observatory magnetograms, recovered from the BGS archives. We correlate recent flares of known X-ray flux against the related *sfe*, taking into account location at the time of the event and use this relationship to estimate the size of the Carrington flare.

SOLAR FLARE EFFECTS

The *sfe* magnetic variation is due to the increased ionisation in the ionosphere that results from the radiation emitted by the solar flare. The enhanced ionospheric conductivity on the day-side of the Earth temporarily effects the *Sq* current system. The *sfe* at a particular site depends on its location relative to the equatorial electrojet and the *Sq* foci (Rastogi *et al.*,1999). However, Eleman (1961) and Curto *et al* (1994) showed that the foci of the *sfe* current system is displaced with respect to the *Sq* system, so it is not always true to assume that the *sfe* is the result of increased *Sq*.





<table>
<tr><th rowspan="2">OBS</th><th rowspan="2">Lat (° N)</th><th rowspan="2">Lng (° E)</th><th rowspan="2">Geomagnetic Lat (° N)</th><th colspan="3">sfe</th></tr>
<tr><th>ΔH (nT)</th><th>ΔD (')</th><th>ΔB_H (nT)</th></tr>
<tr><td>GRW</td><td>51.477</td><td>0.000</td><td>54.00</td><td>-110</td><td>-17.0</td><td>139.6</td></tr>
<tr><td>KEW</td><td>51.467</td><td>359.683</td><td>53.95</td><td>-130</td><td>-13.2</td><td>146.2</td></tr>
</table>

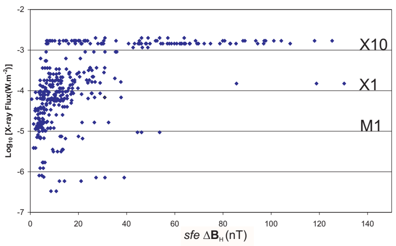
Greenwich *sfe* values are hand scaled from original magnetograms. Kew *sfe* values are as reported by Stewart (1861).
The geomagnetic latitudes given are approximations based on geomagnetic latitude back to 1900 using the IGRF and relating this to measured inclination annual mean values over the period.

These results place the Carrington *sfe* amongst the largest ever recorded.

In a related study, Cliver and Svalgaard (2004) conservatively concluded that the Carrington flare was greater than X10. Boteler (2006) suggests that it may have been of similar magnitude to the largest recorded solar flare, which occurred on 4 November 2003, saturating the GOES X-ray sensor, but estimated by Thomson *et al* (2005) to be X45. The resulting *sfe* from this event at Victoria observatory was 100 nT in *H* and so less than the Kew and Greenwich *sfe* for the Carrington flare. This comparison is reasonable since the local time for the X45 *sfe* was similar to GMT at the time of the Carrington event and latitudinally the locations are also similar.

DATA

A data base of more recent events is constructed from: existing *sfe* data on-line; observatory yearbooks; Ebro observatory lists; additional scaling of events using one-minute values from various INTERMAGNET and WDC magnetic observatories; and GOES X-ray flux data. The *sfe* data collected were either of variations in *H* and *D* or of *X* and *Y*. From these the variation in the magnetic field vector in the horizontal plane (ΔB_H) for each *sfe* has been calculated.

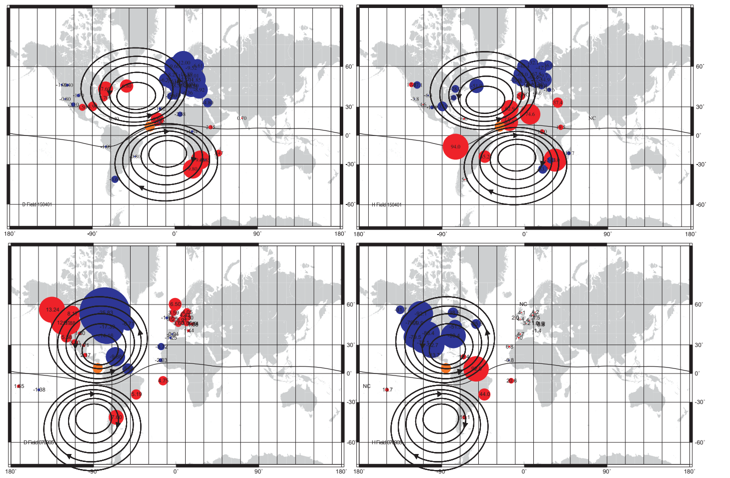


The plot shows each *sfe* plotted against the corresponding X-ray flux. The horizontal lines of data highlight the need to account for other factors, such as the location of each *sfe* measurement.

RECENT LARGE X-RAY FLARES

Four (relatively) recent large flares of known X-ray flux were analysed. These are:

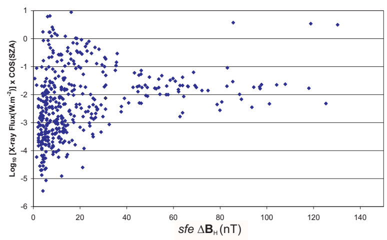
X20	on 2nd April 2001
X14.4	on 15th April 2001 (see below)
X28 (or X45)	on 4th Nov 2003
X17	on 7th Sept 2005 (see below)



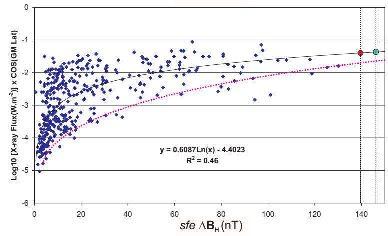
D (left) and *H* (right) *sfe* measurements are plotted on the maps as filled circles with the size representing the *sfe* magnitude. Blue indicates -ve variation and red +ve. The orange circle shows the position of the sub-solar point at the time of the flare. The magnetic dip equator (from the IGRF) is also shown. The ellipses have been included as a guide to indicate the sense of the *Sq* current system, with the arrows showing the direction of current flow. They are hand drawn and not based on a real or modelled system.

X-RAY FLUX and OBSERVATORY LOCATION

It has been stated that *sfe* intensity varies inversely with the solar zenith angle (sza) (e.g. Cliver and Svalgaard, 2004). Taking this into account, the top plot shows all *sfe* data against the corresponding X-ray flux as a function of sza. Although the "horizontal features" disappear the relationship is still not clear.



By plotting the data as a function of geomagnetic latitude (bottom) a clearer pattern emerges. The black line represents the best fit with the relationship shown. The red point is the *sfe* at GRW from which a value of X42 is obtained for the Carrington flare. The green point is the *sfe* at KEW, which corresponds to X48. The pink dotted line is hand drawn to indicate a possible minimum level - approximately X15 for the Carrington flare.



CONCLUSIONS

In general our estimate of soft X-ray magnitude increases with increased *sfe* magnitude but it is critical for the measurement to be at the right place relative to the *Sq/sfe* current systems.

We estimate the Carrington flare to be no less than ~X15 and believe that it is more likely to be ~X42. It is important to note that small deviations in both the geomagnetic latitude and in the *sfe* scaling result in large deviations in the predicted X-ray flux.

This is work in progress. We need to better understand the influence and inherent errors of different parameters. The spatial variation of *sfe* is found to be most clear with geomagnetic latitude but, more detailed analysis of individual events is required.

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