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S. A. L. Maftunzada
Faryab University, Maymana, Afghanistan
e-mail: latif.maftunzada@gmail.com

Definition of physical parameters of 8 X-class solar flares

Abstract. We observed top 8 X-class solar flares registered in the period May 1998 – May 2015. We measure physical parameters of 8 solar flares, such as the temporal scale, size, and magnetic flux density, and find that the sizes of flares tend to be distributed more broadly as the GOES class becomes weaker and that there is a lower limit of magnetic flux density that depends on the GOES class. We also made a brief analysis of solar flares registered in these days, also has shown the duration of time and peak of solar flares in Universal time. We have identified several physical quantities of solar flares and estimated reconnection rate of solar flares. To determine the physical parameters we used images taken with the AIA instrument on board SDO satellite at wavelengths 131 Å, 174 Å, 193 Å, 211 Å, 335 Å, 1600 Å, 1700 Å, 4500 Å, SXT – pictures, HMI Magnetogram, SOLIS Chromospheric Magnetogram, GOES XRT-data. Using the observed values, we calculate reconnection inflow velocity, coronal Alfven velocity, and reconnection rate. The inflow velocities vary from a few kilometers per second to several tens of kilometers per second, and the Alfven velocities in the corona are in the range of 10^3 to 10^4 kilometers per second. As a result, the rate of reconnection is 10^{-3}. We find that the reconnection rate in a flare tends to decrease as the GOES class of the flare increases.

Key words: solar flares, X-rays, reconnection rate.

Introduction

Across the electromagnetic spectrum, flares have a broad variety of effects. They emit x-rays and ultraviolet radiation during a pulse, suggesting extremely high temperatures. Radio waves demonstrate that a small fraction of particles are accelerated to high energies. Synchrotron radiation, which is generated by electrons spiraling along magnetic field lines, accounts for the majority of the radiation. The flux of high-energy particles and cosmic rays on Earth is also increased by intense flashes. Magnetic storms on Earth usually occur 36 hours after a flare on the Sun. The most popular theory is that the solar wind is amplified, compressing the magnetosphere and raising the magnetic field at the Earth's surface. Solar flares form when the direction of the local magnetic field suddenly shifts. The alternative reason for the rapid release of energy in bursts is magnetic reconnection [1].

Solar flares are one of the most strong and energetic phenomena in the solar atmosphere. Due to their importance in the energy balance of the solar corona and their work playing an important role in space weather, several observations investigated the release of energy and induction of solar flares based on solar activity. National solar observatories provide a wealth of data to the overall network, spanning long time periods (e.g., Solar and Heliospheric Observatory, SOHO), multiple perspectives (Solar Terrestrial Relations Observatory, STEREO), and returning a large amount of data (Solar Dynamics Observatory, SDO). Specifically, the huge amount of SDO data are accessible only from a few repositories, such type of data as a full-cadence data or full-disk of scientific concern are hard to download, because of their size.

Solar flares are large "explosions" that occur as a sudden brightening of the Sun's atmosphere over active areas (sunspot groups). They live in the chromosphere and corona, but the most powerful ones can also increase the photosphere's temperature (producing a flare visible even in white light). Richard Carrington, who was drawing sunspots at the time, found two bright spots in one of the sunspot classes and called it a solar flare. In just ten minutes, they brightened and faded. Carrington had already noted that this phenomenon was accompanied the next night by the emergence of the northern lights. In the last century, less than a hundred of these white-flares have been discovered.

In the short wavelength range, the brightening is even more pronounced (UV and X-ray). The Sun's total ultraviolet radiation increases by a significant factor during a flare, while the amount X-ray radiation increases by orders of magnitudes [2].

Solar flares are massive solar explosions that carry energy, light, and high-speed particles into space. These flares are often linked to coronal mass ejections, which are solar magnetic storms (CMEs). The number of solar flares increases every 11 years, and the sun is currently approaching another solar maximum, which will most likely occur in 2013. This means there would be more flares, some small and some large enough to send radiation all the way to Earth.

Based on a classification scheme that distinguishes solar flares according to their frequency, the most powerful flares are classified as "X-class flares." A-class (near background levels) is the smallest, followed by B, C, M, and X. Each letter reflects a 10-fold increase in energy production, similar to the Richter scale for earthquakes. As a result, an X is ten times an M and one hundred times a C. Within each letter class there is a finer scale from 1 to 9 [3-6].

Earth is not affected by C-class and smaller flares because they are too tiny. M-class flares can trigger brief radio blackouts and minor radiation storms at the poles, putting astronauts in risk. [7-8].

The most powerful flare ever measured with modern methods occurred in 2003, during the last solar maximum, and it was so powerful that the sensors measuring it were overloaded. The massive solar X-ray flare that occurred on November 4th was estimated to be an X28. This is a new record-breaking X-ray flare, the most powerful in recorded observational history.

In this work we have identified several physical quantities of X-class solar flares and estimated reconnection rate of X-class solar flares. We have analyzed top 8 strongest solar flares registered from the period May 1998 – May 2015.

Table 1 – Strongest solar flares since May 1998 [6].

№	GOES class	Date	Region	Start	Maximum	End
1	**X3.1**	2014/10/24	2192	21:07	21:41	22:13
2	**X3.1**	2002/08/24	0069	00:49	01:12	01:31
3	**X3**	2002/07/15	0030	19:59	20:08	20:14
4	**X2.8**	2013/05/13	1748	15:48	16:05	16:16
5	**X2.8**	2001/12/11	9733	07:58	08:08	08:14
6	**X2.8**	1998/08/18	8307	08:14	08:24	08:32
7	**X2.7**	2015/05/05	2339	22:05	22:11	22:15
8	**X2.7**	2003/11/03	0488	01:09	01:30	01:45
9	**X2.7**	1998/05/06	8210	07:58	08:09	08:20
10	**X2.6**	2005/01/15	0720	22:25	23:02	23:31

Data analysis

The magnetic energy contained in the solar atmosphere may explain the amount of energy E_{flare} emitted during a flare [9],

$$E_{flare} \sim E_{mag} = \frac{B_{cor}^2}{8\pi} L^3 \quad (1)$$

where L is the characteristic size of the flare and B_{cor} is the characteristic magnetic flux density in the corona [10-13]. Since the released magnetic energy equals the energy flowing into the reconnection field, the energy release rate can be expressed as

$$\left|\frac{dE_{mag}}{dt}\right| \sim 2\frac{B_{cor}^2}{4\pi} V_{in} L^2 \quad (2)$$

where V_{in} is the inflow velocity of the plasma. Therefore, the time required for the energy inflow to supply the flare energy is estimated as

$$\tau_{flare} \sim E_{flare}(\left|\frac{dE_{mag}}{dt}\right|)^{-1} \sim \frac{L}{4V_{in}} \quad (3)$$

and this should be the timescale of the flare. We can measure the inflow velocity V_{in} using this timescale as

$$V_{in} \sim \frac{L}{4\tau_{flare}} \tag{4}$$

To calculate the nondimensional reconnection rate $M_A \equiv \frac{V_{in}}{V_A}$, we must first calculate the Alfven velocity $V_A = \frac{B_{cor}}{(4\pi\rho)^{1/2}}$ in the inflow region: As a result, we can calculate inflow velocity V_{in}, Alfven velocity V_A, and reconnection rate M_A by measuring the coronal mass, the flare's spatial scale L, the magnetic flux density in the corona B_{cor}, the coronal density ρ, and the flare's timescale τ_{flare}, [14-15].

The Geostationary Operational Environmental Satellite, or GOES [5], keeps track of solar flares in real time. Satellites GOES 13, GOES 14, and GOES 15 provided data on electrons, protons, and X-rays [5-6].

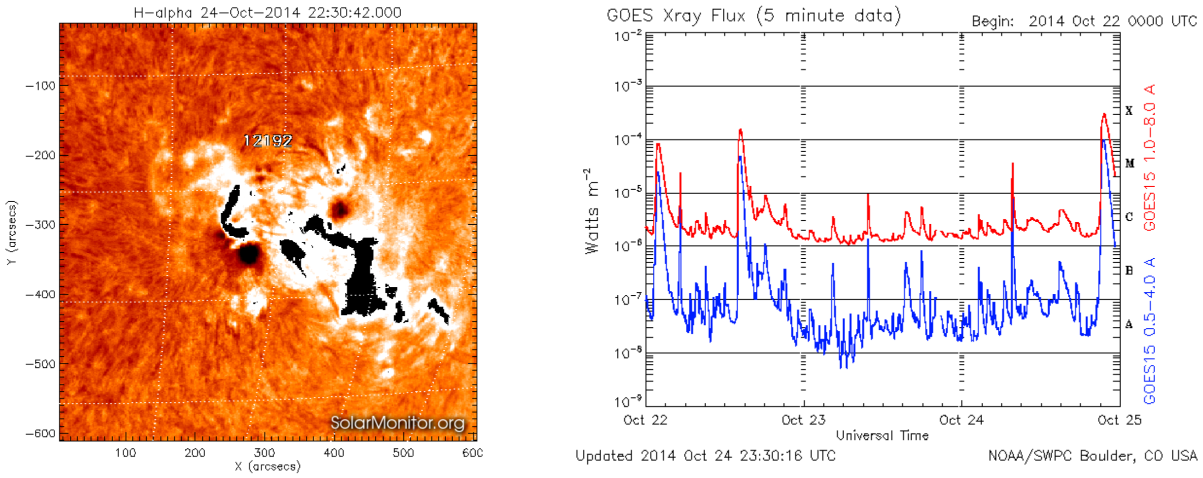

Figure 1 – Active area 12192 (GHN Hα) and the total X-ray flux obtained in GOES 13 and GOES 15 [5]

In Fig. 1 shown the images obtained on the board of Hinode satellite in XRT (October 24, 2014, X3.1). To determine the length of the loops, we used SXT images. The length of the loops can be calculated using the SXT data. The total flux of X-rays and an electron, which was registered on October 24, 2014, is shown in Fig. 2.

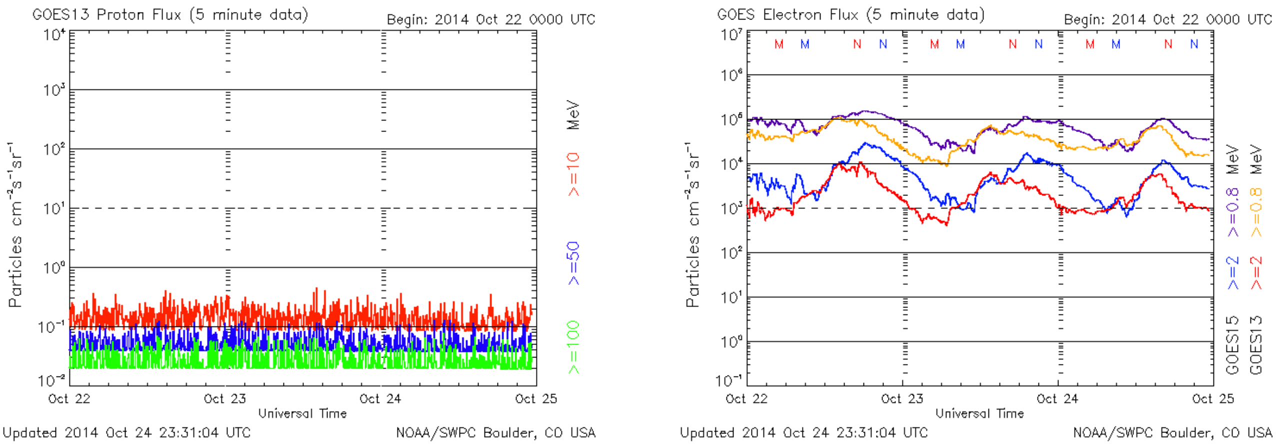

Figure 2 – Total proton and electron flux obtained in GOES 13 and GOES 15 [5]

Results

Using the above described method, we analyzed 8 X-class solar flares that have been registered 1998-2015 years. The reconnection rate was examined in relation to the GOES class of solar flares. The flare parameters obtained in this study are summarized in Table 2.

There is a weak correlation between the timescale τ_{flare} and the GOES peak flux (Fig. 3a). The characteristic size of flares, L, shows a larger scatter when the GOES peak flux is smaller (Fig. 3b). Figure 4 shows the dependence of the reconnection rate M_A from GOES class.

Table 2 – Parameters of the flares

Date	Active region	GOES class	$\tau(s)$	$L(cm)$	$V_{in}(cm \cdot s^{-1})$	M_A	$E_{flare} / \tau(erg \cdot s^{-1}$
2014/10/24	2192	X3.1	2040	2,18E9	2,67E5	3,33E-4	4,05E27
2002/08/24	0069	X3.1	1380	2,1E9	3,81E5	4,76E-4	5,41E27
2002/07/15	0030	X3	540	2,83E9	1,31E6	1,63E-3	3,36E28
2001/12/11	9733	X2.8	600	1,89E9	7,85E5	9,81E-4	8,97E27
2015/05/05	2339	X2.7	360	3,19E9	2,22E6	2,77E-3	7,25E28
2003/11/03	0488	X2.7	1260	1,96E9	3,88E5	4,85E-4	4,78E27
1998/05/06	8210	X2.7	660	1,16E9	4,39E5	5,49E-4	1,9E27
2005/01/15	0720	X2.6	2220	1,38E9	1,55E5	1,94E-4	9,46E26

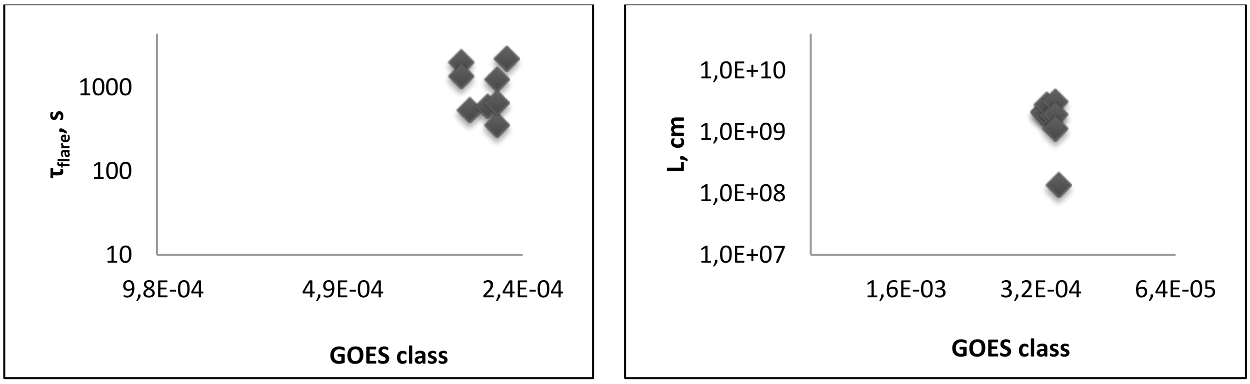

Figure 3 – Physical parameters of each flare plotted against the GOES class. (a) Timescale τ_{flare} . (b) Size L.

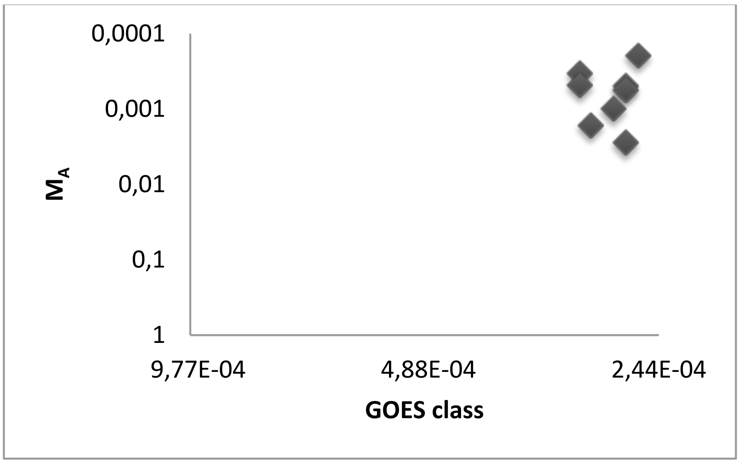

Figure 4 – Reconnection rate M_A plotted against GOES class.

Conclusion

As a result of the sudden flash, the flux of high-energy particles and cosmic rays increases on Earth. Magnetic storms on Earth typically occur 36 hours after a flare event on the Sun has been detected. The amplification of the solar wind, which compresses the magnetosphere and raises the magnetic field at the Earth's surface, is the most common explanation. Solar flares arise in areas where a sharp change in the direction of the local magnetic field occurs. The reconnection rate values are distributed in a range from to $10^{-4}-10^{-3}$. As the GOES class increases, the value of the reconnection rate decreases. The reconnection rate obtained in this study is within one order of magnitude of the Petschek model's predicted maximum value [13].

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