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Two different approaches to the observation of solar flares: Science or forecasting?

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Summary. — Solar flares are the main sources of acceleration of energetic particles from the solar atmosphere through the Heliosphere to the circum-terrestrial Environment. At present, several space-born telescopes in collaboration with small, medium and large class telescopes provide plenty of data at the different wavelengths and resolutions, which allow us to study these phenomena in detail. In this review, I describe some of the recent results obtained in the international context by our Italian community concerning the study of the mechanisms at the base of the storage and release of free energy in solar flares. I highlight the main aspects which characterize two different approaches to the observation of the flares: the attempt to provide a further contribution to the physics of the processes involved by such events and the answer to the increasing request of forecasting in order to prevent the damage to the technological systems which permeate our life. Both approaches require a vision as complete as possible of the whole solar atmosphere and synergies among different methods of analysis.

1. – Introduction

The solar cycle 24 has been rather weak, particularly concerning the number of sunspots. Nevertheless, one of the most powerful outbursts of flare activity occurred during the decline phase of the cycle in early September 2017. Within one week, the super AR NOAA 12673 produced more than 40 C-class flares, 27 M-class flares, and 4 X-class flares. Among these events we observed the strongest flare of the cycle: an X9.3 class flare. Several halo coronal mass ejections (CMEs) were recorded and their effects on the terrestrial environment were several solar energetic particle events including one ground-level enhancement (GLE) on September 10, as well as strong geomagnetic storms (GMSs) and Forbush decreases (FD) in galactic cosmic ray flux ([1]). In particular, two X-class flares occurred on Sept 6 are really interesting because they are also white light flares (WLFs), i.e. a continuum emission has been observed some minutes after the first appearance of the ribbons at the chromospheric level and before the peaks of the X-rays, EUV, and Hα lines ([2]).

This phase of activity of the Sun has been also paradigmatic for its strong effects in the geospace. Many of these flares have been accompanied by Earth-directed halo CMEs. A first interplanetary CME (ICME) driven shock derived from a first eruption occurred on Sept 4 arrived at Earth at approximately midnight on Sept 6, after 50 h from the flare, and brought an interplanetary magnetic field (IMF) with a positive vertical field of 15 nT. For this reason a FD approximately equal to 2% and almost no GMS occurred because the Bz magnetic field component in front of the corresponding ICME was northern. Instead, the shock of a second ICME, associated with the X9.3 flare produced larger disturbances (FD 9.3% and GMS with indexes Dst 144 nT, Ap 235) because the second ICME overtook the trailing part of the first ICME near Earth, and the resulting Bz component was more intense and southern.

The activity in early September 2017 can be considered particularly interesting not only for its physical aspects but also for its implications in the Space Weather context. These events were characterized by many aspects of the standard flare model: the presence and the important role of a flux rope in the core of the magnetic field system, the observational evidences of particle acceleration downwards to the lower layers of the solar atmosphere, the manifestations of hot flare loops formed as a consequence of the magnetic reconnection, the formation of the CME core in the outer corona, etc. Although all these features sketched in the standard flare model play an important role in the interpretation of the mechanisms which store the magnetic energy and trigger the magnetic reconnection, these kinds of events are still enigmatic for several aspects and their forecast is very difficult.

In this Paper, I describe the contribution of the Italian community to many aspects regarding some of the above mentioned features and the main sources of accumulation of free magnetic energy in corona before the flares. I also describe some of the recent works dedicated to the flare forecasting and I summarize some still open questions about the solar flares and the magnetic field configurations suitable for their trigger.

2. – Observations of main features considered by the standard flare model

One of the crucial feature considered in many models of flares and eruption of filaments is the flux rope, i.e. a particular field topology characterized by a set of magnetic field lines that collectively wrap around a central, axial field line. Often magnetic flux ropes in the low corona are considered the main progenitors of CMEs, where an initial period of stability of the flux rope is followed by a fast and sudden ejection outwards into interplanetary space. The importance of the boundary conditions for erupting magnetic flux ropes has been considered by [4]. They coupled two different modeling techniques, a quasi-static non-potential evolution model and MHD simulations to follow the formation and loss of equilibrium of magnetic flux ropes up to 4 solar radii. In their simulations the onset of eruption occurs once the tension of the overlying arcades is insufficient to hold down the underlying flux rope. This work represents also an interesting tool to forecast the arrival time and properties of CMEs at the Earth's magnetosphere.

The role of the overlying magnetic field has been investigated also by [5]. The comparison between two ARs, characterized by a different magnetic field configuration, showed a different behavior in the accumulation of the magnetic helicity flux in the corona, depending on the location of the flux ropes and the overlying field. The complexity and strength of the photospheric magnetic field is only a partial indicator of the real likelihood of an AR producing eruptive flares. This confirms that for the occurrence of CMEs associated with ARs, it is important not only the presence of a flux rope, but also the configuration of the surrounding magnetic field.

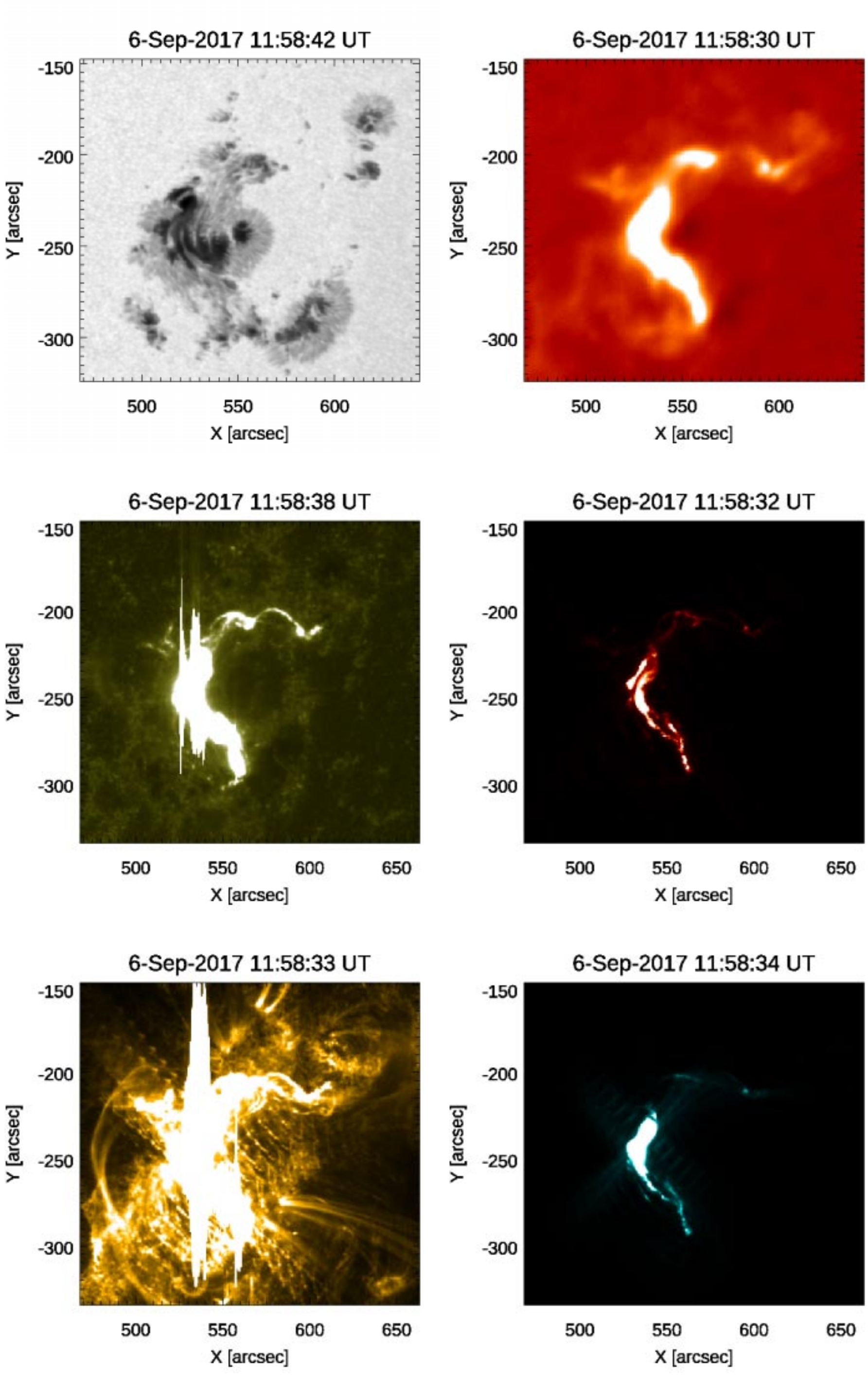

Fig. 1. – Images of the strongest flare of the solar cycle 24 taken during its peak at different wavelenghts: in the continuum by HMI/SDO (top left panel), in Hα by the GONG network (top right panel), at 1600 Å (middle left panel), at 304 Å (middle right panel), at 171 Å (bottom left panel) and at 131 Å by AIA/SDO (bottom right panel).

The role of the ambient field and its action is described also by the decay index in the context of the torus instability. Assuming an external field B_{ext}, the decay index n is defined as $dlnB_{ext}/dlnR$, where R is the major radius of the flux rope ([6]). The torus instability model predicts that a magnetic flux rope undergoes an eruption when its axis reaches a location where the decay index of the ambient field is larger than a critical value (n_{crit} = 1.5 for [6]). In this regard, [7, 8] showed that there is a critical range of [1.3–1.5], rather than a critical value for the onset of the torus instability. This range is in good agreement with the predictions of the current-wire model, despite the inclusion of line-tying effects and the occurrence of tether-cutting magnetic reconnection.

Other recent interesting investigations concern the studies of the so called recurrent flares, which provide the opportunity to describe series of events with significant impact on Earth environment. [9] analysed three confined C-class flares (C1.0, C2.0 and C4.7), and compared the results with the observations of the last M1.8 class eruptive flare. In this case, all the recurrent flares occurred within a short period of time (about 3 hours) and showed a very similar plasma morphology and magnetic field configuration. The non linear force free extrapolations allowed to attribute the activation of the magnetic structure not to the existence of a 3-D null point in the corona, as for the AR NOAA 12673, but by a peculiar bald patch reconnection with a pseudo-fan and pseudo-spine (see also [10]).

In order to shed light on the occurrence of recurrent flares and subsequent associated CMEs, [11] studied the AR NOAA 11283 where 4 recurrent M and X GOES-class flares occurred. Using vector magnetograms taken by HMI/SDO they calculated the horizontal velocity fields of the photospheric magnetic structures, the shear and the dip angles of the magnetic field, the magnetic helicity flux distribution, and the Poynting fluxes across the photosphere due to the emergence and the shearing of the magnetic field. The main result was that these recurrent flares were powered by the energy initially present in the magnetic field system, while the shearing motions were the trigger mechanism of its release.

3. – The accumulation of the free magnetic energy prior to the flares

We can consider basically three main mechanism of accumulation of free magnetic energy in corona: the photospheric horizontal motions, the magnetic flux cancellation and the magnetic flux emergence.

The horizontal motions seem the cause of the magnetic field configuration at the base of the X-class flares occurred on Sept 2017. Peculiar horizontal displacements of the negative umbra of the delta spot of the AR have been observed for several hours with velocity up to 0.6 km s^{-1}, using the Differential Affine Velocity Estimator for vector magnetograms by [2]. Moreover, the horizontal motions seem also the cause of the formation of two related 3D null points located in very low corona that are most likely responsible for the triggering of the X2.2 and X9.3 GOES class flares occurred on Sept 6 (see [12]). The low heights above the photosphere of these 3-D null points seem to explain their contribution in the continuum emission.

A second mechanism usually proposed in literature to determine the magnetic field configuration suitable to deliver the free energy in corona is the flux cancellation. On this regard, I wish to report the work of [3] who observed converging motion of the opposite polarities, which results in flux cancellation near the Polarity Inversion Line (PIL), followed by a jet-like ejection below the filament main axis. The observed brightening seems to be due to the reconnection that occurred in the lower layers of the solar atmosphere and might be a signature of the tether-cutting mechanism.

Unfortunately, we do not have recent contributions of the Italian solar community to the observation of flares which seem to be driven by the emergence of new magnetic flux.

4. – Approach to the Space weather and flare forecasting

The approach to understand the flare occurrence form a point of view of their forecasting can be schematically divided in two different methods: the parametrization of the observational solar data to characterize the active regions, sites of flare occurrence, and the statistical method by which prior parameters or flaring activity are used to evaluate particular target parameters and predict whether or not it is going to flare. A variety of statistical methods are employed to produce the forecasts from the parametrizations (see [13] for details).

Recently, [14] applied some machine learning methods considering more than 150 parameters and producing a reliable ranking of the weights with which the data properties contribute to the forecast.

The observatories of Turin and Catania and the University of Tor Vergata (Rome) implemented some services to forecast flares and CMEs. In particular, INAF - Catania Astrophysical Observatory provides daily indications of the probabilities that each sunspot group visible on the solar disc may host solar flares of C-, M- and X- class (see [15]).

All these forecasting systems represent a first step in the direction of useful and complete tool which could provide interesting information about the potential impact of the solar events for circum-terrestrial Environment.

A first attempt of the Italian community to provide a comprehensive analysis of a Geoeffective solar event has been conducted by [16]. A full halo CME has been described from when it left the Sun on 21 June 2015 from AR NOAA 12371 to 22 June 2015 when it encountered the Earth and generated a strong geomagnetic storm. The effects on the magnetosphere, plasmasphere, and ionosphere have been analysed. This work represents a useful example of the importance of a multi-instrument, multi-wavelength and multidisciplinary approach to the flares and their effects.

5. – Conclusions

The long tradition of the Italian community to the study of the solar eruptions form the observational point of view and the growing activity of the theoretical analysis of these events is showing many results and interesting contributions not only to the knowledge of many physical aspects of the flares, but also to the efforts of extending the horizon of future space weather forecasting capabilities.

However, models and simulations of flares are still using highly idealized field structures and invoking very artificial lower boundary conditions to represent the driving perturbations on the photosphere. Also simulations of the dynamic evolutions are critically effected by the process of magnetic reconnection whose physics is not well represented in current numerical simulations. Therefore, several questions remain open. Here, I report some of them:

- Do flux ropes exist quiescently in the corona prior to the CME?
- If they exist quiescently in the corona, are they formed from emerging twisted magnetic flux, or from photospheric motions?

- Is the role of the surrounding magnetic field important to determine the conditions for the flare occurrence?
- Is the monitoring of the photosphere evolution so important for the knowledge of the coronal magnetic configurations suitable for the flare occurrence?
- Where does the main energy release occur and where are the key regions that are involved?
- How can we exploit both the detailed case studies and the statistical approaches to got a robust method for flare forecasting?

Certainly, the answers to these questions require further efforts of the scientific community in terms of man power, new advanced technology, new synergies. We hope that in the next future the Italian community will be put in the right conditions to provide a useful contribution to the this research field and to the Space Weather challenges.

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