X-RAY PLASMA EJECTIONS AND THEIR ASSOCIATION WITH OTHER SOLAR-ACTIVITY PHENOMENA

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Abstract. Recently developed in Wrocław, a new catalogue of X-ray Plasma Ejections (XPEs) observed by the Soft X-ray Telescope onboard Yohkoh, is a very useful tool for some statistical studies. We investigated the association of XPEs with solar flares and coronal mass ejections (CMEs). We found that particular subclasses of XPEs show different levels of association. Moreover, flares and CMEs associated with different subclasses of XPEs show distinctly different characteristics. We conclude that the event that we call ‘X-ray Plasma Ejection’ can be a manifestation of different physical processes.

Key words: Sun: corona - flares - Coronal Mass Ejections (CMEs)

1. Introduction

X-ray plasma ejections (XPEs) are sudden expulsions of hot magnetized plasma in the solar corona seen in X-rays. XPEs display a wide range of macroscopic motions showing different morphological, kinematic, and physical conditions. They occur usually during the impulsive phase of flares. Sometimes a given flare produces even more ejections at later times and different locations. XPEs also show a close connection with other solar-activity phenomena: coronal mass ejections (CMEs), prominences, radio bursts, coronal dimmings, and global waves.

XPEs have been systematically observed since 1991 when the Yohkoh satellite began operations (Klimchuk et al., 1994, Shibata et al., 1995), nevertheless some earlier observations are known (e.g., Harrison et al., 1985). A strong inhomogeneity of XPEs as a group suggests different physical mechanisms (magnetic reconnection, magnetic loss-of-equilibrium, others?) responsible for their occurrence.
Although other recent imaging instruments: the Soft X-ray Imager onboard Geostationary Operational Enviromental Satellites (GOES), the Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI), the X-Ray Telescope onboard Hinode, have been providing observations of XPEs, the Soft X-ray Telescope, SXT, (Tsuneta et al., 1991) onboard Yohkoh resulted in the largest database of XPEs until now.

2. The YOHKOH/SXT XPE Catalogue

We recently developed a new catalogue of XPs at the Astronomical Institute of the University of Wroclaw. The catalogue contains records of 368 XPEs observed by the Yohkoh/SXT during the full satellite operation (1991-2001). 163 events out of the 368 were not reported before. The catalogue resides online at [http://www.astro.uni.wroc.pl/XPE/catalogue.html](http://www.astro.uni.wroc.pl/XPE/catalogue.html).

Each record in the catalogue contains MPEG movies illustrating evolution of a XPE, a short qualitative description, results of quantitative analysis (if available), references, and entries to the associated flare and CME. In the case of flares and CMEs we used data from the Yohkoh Flare Catalogue (HXT/SXT/SXS/HXS) – Sato et al. (2006) and the SOHO LASCO CME Catalog (Gopalswamy et al., 2009).

In our catalogue we developed a new classification scheme of XPEs based on three criteria concerning: (a) the morphology of the XPE, (b) its kinematics, and (c) multiplicity of the occurrence. Examining each criterion we distinguish two subclasses of events only: (a) 1 – collimated, 2 – loop-like; (b) 1 – confined, 2 – eruptive; (c) 1 – single, 2 – recurrent. In each criterion the subclass 1 refers less energetic events and the subclass 2 refers more energetic events.

The morphological criterion resolves the direction of the moving soft X-ray plasma in comparison with the local magnetic field. In the case of the subclass 1, the direction is parallel, i.e. along the already existing field lines; in the case of the subclass 2 — perpendicular, i.e. across the already existing field lines (or strictly speaking – together with them).

For the assignment into one of the kinematical subclasses we have chosen a rate of the height increment above the chromosphere, $\dot{h}$. A negative value, $\dot{h} < 0$, means the subclass 1, the opposite case, $\dot{h} \geq 0$ means the subclass 2. XPEs from the kinematical subclass 1 suggest the presence of magnetic or gravitational confinement. For XPEs from the kinematical subclass 2, an
increasing velocity in the radial direction in the field of view of the SXT allows us to anticipate a further expansion leading to irreversible changes (eruption) of the local magnetic field. In consequence, at least a part of the plasma escapes from the Sun.

According to our third criterion we separate unique XPEs that occurred once in time (subclass 1) from recurrent events for which following expanding structures can be seen with time (subclass 2).

By using the classification we were able to separate several subclasses of XPEs that look more homogeneous than the full population. Unfortunately, we are not sure if the particular subclasses of XPEs refer events that are physically different. A closer confirmation would give a quantitative analysis of the soft X-ray images, however for the majority of XPEs in the catalogue this kind of analysis is practically unreliable, due to minor signal and other observational limits. Therefore, the main motivation of our paper is to justify the presence of physically different subclasses of XPEs based on a comparison of the properties of other associated solar-activity phenomena. For events like flares or CMEs their basic characteristics are known well. In Section 3 we present the association of XPEs with flares, in Section 4 we present the association of XPEs with CMEs.

3. Association of XPEs with flares

Recognition of an associated flare for the majority of XPEs in the catalogue is very easy. The flare is seen usually in movies illustrating evolution of the XPE as a strong saturation due to much stronger soft X-ray radiation. In several cases a flare occurred simultaneously with the XPE but in another active region. We considered this flare as the associated event only in case when some distinct magnetic loops connecting both active regions were seen. Finally, there are several XPEs in the catalogue that occurred when no flare was observed on the Sun.

For the associated flares we determined the X-ray class and the total duration basing on light curves recorded by GOES, in the wavelength interval 1-8 Å. We defined the total duration as the interval between a constant level of the solar flux before and after the flare, therefore our values of this parameter are larger than intervals between a start time and end time that are routinely reported in Solar-Geophysical Data.

In Fig. 1 we present a scatterplot of the X-ray class versus the total du-
Figure 1: Scatterplot of the flare X-ray class versus the flare total duration. Flares associated with the subclasses of collimated and loop-like XPEs are marked with crosses and stars, respectively. Small boxes refer to flares associated with XPEs observed with a poor quality or during other problematic circumstances.

This shift is confirmed by medians calculated separately for both groups of flares. As it is seen in Table 1, the median X-ray class of flares associated with loop-like XPEs is three times more than that for collimated XPEs. Similarly, the median flare duration of loop-like XPEs is two times greater than that of the collimated XPEs. Higher X-ray class and longer duration mean a more-energetic flare. Thus we can conclude that more-energetic, loop-like XPEs are associated with more-energetic flares, on average, and the less-energetic, collimated XPEs rather prefer less-energetic flares.

We investigated also the characteristics of flares associated with sub-
Table I: Properties of flares associated with particular subclasses of XPEs

| Classification criterion | XPE subclass | Number of events | Flare class (median) | Flare duration (median) |
|--------------------------|--------------|------------------|----------------------|------------------------|
| I (morphological):       |              |                  |                      |                        |
| 1 (collimated)           | 40           | C6.1             | 51 min.              |                        |
| 2 (loop-like)            | 126          | M1.8             | 110 min.             | x3.0                   |
|                         |              |                  |                      | x2.2                   |
| II (kinematical):        |              |                  |                      |                        |
| 1 (confined)             | 49           | C6.1             | 45 min.              | x3.8                   |
| 2 (eruptive)             | 94           | M2.3             | 120 min.             | x2.7                   |
|                         |              |                  |                      |                        |
| III (recurrence):        |              |                  |                      |                        |
| 1 (single)               | 53           | M1.4             | 75 min.              | x1.5                   |
| 2 (recurrent)            | 65           | M2.1             | 155 min.             | x2.1                   |
| 1+1+1                    | 13           | C5.2             | 42 min.              | x6.0                   |
| 2+2+2                    | 41           | M3.1             | 155 min.             | x3.7                   |

Classes of XPEs defined by our kinematical and recurrence criteria. Medians calculated separately for flares associated with particular subclasses of XPEs, presented in Table 1, show a similar tendency, namely that the association between XPEs and flares is determined by amount of energy that were released in these events. The difference between values of median is higher for flares associated with subclasses of XPEs defined by the kinematical criterion (a factor 3.8 and 2.7 for X-ray class and duration, respectively) than for flares associated with subclasses defined by the recurrence criterion (a factor 1.5 and 2.1 for X-ray class and duration, respectively).

We can expect that a difference between the characteristics that describe associated flares should be even higher for two subclasses of XPEs that we define by combining our three criteria simultaneously. Indeed, medians for flares associated with the subclass 1+1+1 (collimated, confined,...
single XPEs) and subclass 2+2+2 (loop-like, eruptive, recurrent XPEs) show extreme differences (a factor 6.0 and 3.7 for X-ray class and duration, respectively). As it is seen in Fig. 2, the flares associated with the subclass 1+1+1 and 2+2+2 of XPEs are almost separated.

4. Association of XPEs with CMEs

For associating the XPEs from our list with CMEs we used the SOHO LASCO CME Catalog (Gopalswamy et al., 2009). Only 296 XPEs occurred when the LASCO coronagraphs were making observations. We found that 180 XPEs (60.8%) were associated with CMEs. This is slightly lower than the 69% (95 from 137 events) obtained by Kim et al. (2005). We consider a XPE-CME pair as physically connected if the XPE occurred within the position angles defined by the CME angular width increased by 10° from both sides. Moreover, time of XPE occurrence had to fall within 3-hours-interval centered around the extrapolated time of CME start at $h = 1R_S$. 

Figure 2: Scatterplot of the flare X-ray class versus the flare total duration. Flares associated with the subclasses of collimated, confined, single (1+1+1) and loop-like, eruptive, recurrent (2+2+2) XPEs are marked with crosses and stars, respectively. Small boxes refer to flares associated with other XPEs.
Figure 3: Scatterplot of the CME angular width versus the CME linear velocity. CMEs associated with the subclasses of collimated and loop-like XPEs are marked with crosses and stars, respectively. Values are taken from the SOHO LASCO CME catalog (Gopalswamy et al., 2009). Small boxes refer to CMEs associated with XPEs observed with a poor quality or during other problematic circumstances.

For the extrapolation we used the time of first appearance in the LASCO/C2 field of view and the linear velocity taken from the CME catalog.

In Fig. 3 we present scatterplot of angular width versus linear velocity for CMEs associated with morphological subclasses of XPEs, i.e., collimated and loop-like XPEs marked with boxes and stars, respectively. The aggregate number of events is far lower than the total number of events in the catalogue, because we considered only well-observed XPEs that occurred close to the solar limb (|λ| > 60°). Both groups of CMEs are mixed in the plot, however some shift toward wider and faster events is seen for CMEs associated with loop-like XPEs.

This shift is confirmed by medians calculated separately for both groups of CMEs. As it is seen in Table 2, the median for CMEs associated with loop-like XPEs is 2.1 times and 1.4 times greater than the median for CMEs associated with collimated XPEs for CME angular width and CME velocity, respectively. Higher angular width and velocity mean a more-energetic
Table II: Properties of CMEs associated with particular subclasses of XPEs

| Classification criterion | XPE subclass | Number of events | CME angular velocity (median) | CME velocity (median) |
|--------------------------|--------------|------------------|-------------------------------|-----------------------|
| I (morphological):       |              |                  |                               |                       |
| 1 (collimated)           | 13/31 (42%)  | 61°              | 444                           |                       |
| 2 (loop-like)            | 47/71 (66%)  | 126°             | 602                           | x2.1 x1.4             |
| II (kinematical):        |              |                  |                               |                       |
| 1 (confined)             | 16/41 (39%)  | 83°              | 526                           |                       |
| 2 (eruptive)             | 37/48 (77%)  | 126°             | 642                           | x1.5 x1.2             |
| III (recurrence):        |              |                  |                               |                       |
| 1 (single)               | 17/31 (55%)  | 104°             | 518                           |                       |
| 2 (recurrent)            | 24/33 (73%)  | 126°             | 602                           | x1.2 x1.2             |
| 1+1+1                    | 7/14 (50%)   | 61°              | 357                           |                       |
| 2+2+2                    | 20/23 (87%)  | 126°             | 613                           | x2.1 x1.7             |

CME, thus we can conclude that more-energetic, loop-like XPEs are associated with more-energetic CMEs, on average, and the less-energetic, collimated XPEs rather prefer the less-energetic CMEs. Moreover, the loop-like XPEs show better correlation with CMEs than the collimated ones: 66% and 42%, respectively.

We also investigated characteristics of CMEs associated with subclasses of XPEs defined by our kinematical and recurrence criteria. Medians calculated separately for CMEs associated with particular subclasses of XPEs, presented in Table 2, show a similar tendency, namely that the association between XPEs and CMEs is determined by the amount of energy released in these events. The difference between the median values is slightly higher.
for CMEs associated with subclasses of XPEs defined by the kinematical criterion (a factor 1.5 and 1.2 for angular width and velocity, respectively) than for CMEs associated with subclasses defined by the recurrence criterion (a factor 1.2 for both angular width and velocity). More-energetic XPEs better correlate with CMEs than less-energetic subclasses: 77% and 39%, respectively, for kinematical criterion, and 73% and 55%, respectively, for recurrence criterion.

As in case of flares, medians for CMEs associated with the subclass 1+1+1 (collimated, confined, single XPEs) and subclass 2+2+2 (loop-like, eruptive, recurrent XPEs) show extreme differences (a factor 2.1 and 1.7 for angular width and velocity, respectively). The subclass 2+2+2 shows the strongest correlation with CMEs (87%), whereas the subclass 1+1+1 – only 50%.

5. Discussion and Conclusions

Our investigation shows that the characteristics of flares and CMEs associated with particular subclasses of XPEs are different. We found that the scale of differences is higher for flares than for CMEs. We also found that the morphological and kinematical criteria proposed in our classification scheme of XPEs separate better the associated events than the recurrence criterion (compare the boldfaced lines in Tables 1 and 2).

The results strongly suggest that the total amount of energy, converted from the magnetic field in the active region during its magnetic reconfiguration, determines the characteristics of events like: flares, CMEs, XPEs, which are common consequences of this reconfiguration. Thus, more-energetic XPEs are associated with more-energetic flares and CMEs and less-energetic ones – seem to occur commonly. This statistically averaged picture has exceptions in the partitioning of the magnetic energy.

We have shown that the subclasses of XPEs separated on the basis of our simple observational criteria have different levels of correlation with other solar-activity phenomena. The difference is also seen if we consider the basic parameters describing these flares and CMEs. However, the association of XPEs with different flares or CMEs does not mean a specific eruption mechanism as long as these flares or CMEs do not represent physically different groups. The everlasting discussion concerning the reality of existence of two different groups of flares (compact vs. arcade, e.g., Pallavicini et al.,
1977) or CMEs (accelerated vs. constant, e.g., Andrews & Howard, 2001) is crucial in this context.

A careful inspection of many movies in the XPE catalogue suggests different solutions. For example, the collimated XPEs seems to be connected more directly with the reconnection process (reconnection outflow, chromospheric evaporation), whereas the loop-like XPEs are connected rather with a loss-of-equilibrium of magnetic structures. In some examples occurs also a leakage of plasma due to the plasma-$\beta$ parameter approaching unity.

For a more precise separation of physically different subclasses of XPEs a quantitative analysis of the XPE observations is necessary (see Tomczak & Ronowicz, 2007).

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