HOT AND COOL PLASMA EJECTIONS IN THE SOLAR CORONA

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Abstract. We present the results of the first attempt of statistical research devoted to the association between X-ray Plasma Ejections (XPEs) and prominences. For this aim, we compared contents of a catalogue of XPEs, observed by the Soft X-ray Telescope onboard Yohkoh, to Hα reports from the Solar-Geophysical Data. We found that only less than one third of XPEs shows a low-temperature counterpart. A modest connection between hot and cool plasma motions in the corona is also supported by frequent discrepancy between morphology and kinematics of simultaneously occurring XPEs and prominences. We explain the poor correlation (20-30%) between XPEs and prominences and high correlations (∼70%) between these phenomena and CMEs as a proof of existence of two separate subclasses of CMEs.

Key words: Sun: corona - X-ray Plasma Ejections (XPEs) - prominences

1. Introduction

Eruptive phenomena observed above the solar surface have been continuously attracting attention for many years. Due to their rapid evolution and plenty of possible configurations, they are the most spectacular events on the Sun. Moreover, eruptive phenomena play a crucial role in shaping terrestrial space weather. The solar magnetic field – continuously evolving in countless episodes of generation, reconfiguration, and decay – is responsible for plenty of events observed in different temporal and spatial scales in a broad range of wavelengths. There are three main classes of events: prominences, coronal mass ejections (CMEs), and X-ray plasma ejections (XPEs).

Prominences are relatively cool and relatively dense parts of the solar atmosphere routinely observed in the hydrogen Hα line in many ground-based observatories. They are known since 1860's (Secchi, 1875). Among
many phenomenological classifications organizing a heterogeneous world of prominences (Tandberg-Hanssen, 1995), the kinematical one (de Jager, 1959) resolving quiescent and moving events seems to be the most useful.

CMEs are sudden, large-scale expulsions of magnetized plasma observed high in the corona and in the heliosphere. Since a launch of the first space white-light coronagraph (Tousey, 1973), we can detect the photospheric light scattered by electrons kept within expanding magnetic structures. Recently operating coronagraphs onboard the SOHO and STEREO satellites derive continuously new examples of well-observed CMEs.

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. XPEs have been systematically observed since 1991 when the Yohkoh satellite began operations (Shibata et al., 1995). A strong inhomogeneity of XPEs as a group suggests different physical mechanisms responsible for their occurrence.

2. Association between eruptive phenomena

We summarize schematically basic features of solar eruptive phenomena in a diagram temperature vs. height (Figure 1). Even this simple illustration teaches us that simultaneously occurring events belonging to different classes may be somehow associated one to another, responding a reconfiguration of magnetic field in the solar atmosphere. Therefore, statistical investigation combining lists of events detected by particular instruments is very useful for better understanding of this complex problem.

Observations suggest a good correlation of moving prominences with CMEs. For the 54 these prominences observed at the Mauna Loa Solar Observatory (MLSO) between 1996 February and 1998 June, Gilbert et al. (2000) found 36 associated CMEs observed by the LASCO coronagraphs onboard SOHO or by the Mark-III coronametr at the MLSO, which gives a 67% correlation. Particular subclasses of prominences show different levels of the correlation: 94% (17 from 18 events) for eruptive prominences, 70% (7 from 19 events) for disappearing filaments, and 46% (12 from 26 events) for active prominences.

Gopalswamy et al. (2003) compared a list of 186 moving prominences, observed in the years 1996-2001 by the Nobeyama Radioheliograph, to the
SOHO LASCO CME Catalog (Gopalswamy et al., 2009). They found 134 associated events, i.e. a 72% correlation. They found also that the prominences that move radially (a feature of eruptive prominences) show a 83% correlation (126 from 152 events), whereas the prominences, which move transversally (a feature of active prominences) show a 24% correlation (8 from 34 events).

A similarly close association between XPEs and CMEs was reported. Kim et al. (2005) compared a list of 137 XPEs, observed between 1999 April and 2001 March by the SXT telescope (Tsuneta et al., 1991) onboard Yohkoh, to the SOHO LASCO CME Catalog. They found 95 associated events, i.e. a 69% correlation. They found also a morphological dependence of the CME association: a 100% correlation (for 11 events) for jet-type XPEs, a 77% correlation (46 from 60 events) for loop-type XPEs, a 70% correlation (28 from 40 events) for spray-type XPEs, and a 28% correlation (5 from 18 events) for confined XPEs.

Tomczak & Chmielewska (2012) checked up the full list of XPEs observed by the SXT/Yohkoh, when the LASCO coronagraphs were opera-
tional, and found that 182 XPEs from 275 were associated with CMEs. It gives a 66% correlation. For different subclasses of XPEs established morphologically and kinematically they found a broad range of correlation between 44% and 88%.

An association between XPEs and prominences has been poorly investigated until now. There are only a few papers, in which this relation was monitored for singular events (Gopalswamy et al., 1997; Maričić et al., 2004; Vršnak et al., 2004; Ohyama & Shibata, 2008; Kim et al., 2009). These works show that relation between hot and cool plasma ejections can be complex and cannot be considered as a substitute of statistical works.

The only statistical research was performed by Akiyama & Hara (2000) for a time of a low solar activity. They studied the association between flares, XPEs, and prominence eruptions in 1996 using the Yohkoh/SXT images and the Hα reports from the Solar-Geophysical Data (SGD). They found that 12 from 29 flares observed in the Hα line were associated with XPEs. 16 flares were physically connected with prominence eruptions, 6 flares were associated with both erupting phenomena, an XPE and a prominence.

3. Association of XPEs with prominences

Our intention was to make the first attempt of statistical research devoted to the association between XPEs and prominences for a time interval longer than one year. In our studies we used a catalogue of XPEs that resides online at http://www.astro.uni.wroc.pl/XPE/catalogue.html. The catalogue contains records of 383 XPEs observed by the Yohkoh/SXT during the full satellite operation (1991-2001) and is corrected and upgraded regularly. Tomczak & Chmielewska (2012) gave a detailed description of the catalogue as well as a statistical study of its content.

For each event from the XPEs catalogue we looked for an Hα counterpart in a list of active prominences and filaments collected in comprehensive reports of the SGD. In order to check a temporal association between a prominence and an XPE, we required time of the XPE occurrence to fall within 3-hours-interval centered around the first observation time of the prominence. In order to check a spatial association, we required the XPE occurrence within the same active region as the prominence.

We obtained that only 93 from 356 XPEs (26%) were associated with prominences. For well-observed XPEs (so-called quality A or B in the c-
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(analysis) this correlation is slightly better: 64 from 208 events, i.e. 31%.

It should however be stressed that the data taken from the SGD are very inhomogeneous, because they come from different observatories. There is also lack of information concerning the time periods, in which none of the observatories monitored the Sun. These limits may be responsible for lowering the rate of the association between XPEs and prominences.

Therefore we compared also events from the XPEs catalogue to a list of 186 moving prominences published by Gopalswamy et al. (2003). They used microwave observations taken by the Nobeyama Radioheliograph (Nakajima et al., 1994) at 17 GHz in the years 1996-2001. From 65 limb XPEs that occurred in the years 1996-2001 during “duty hours” of the Nobeyama Radioheliograph (22:30-06:30 UT) only 13 events had its microwave counterpart, i.e. 20% of events.

To recognize subclasses of XPEs that better correlate with prominences, we used a classification scheme developed in the catalogue. It bases on three criteria concerning: (a) the morphology of the XPE, (b) its kinematics, and (c) multiplicity of the occurrence. For each criterion we distinguish two subclasses of events: (a) collimated/loop-like; (b) confined/eruptive; (c) single/recurrent.

In our work we used only the criteria (a) and (b), because the data from the SGD does not inform about multiplicity of the prominence occurrence. 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 leads to irreversible changes (eruption) of the local magnetic field. In consequence, at least a part of the plasma escapes from the Sun.

Table I summarizes the correlation with prominences for particular subclasses of XPEs. As we see, the association can vary from the average value reaching only about 20% for confined XPEs and almost 50% for well-
Table I: The correlation with moving prominences for particular subclasses of XPEs

| XPE subclass       | Number of XPEs | Number of associated prominences | Rate(%)     |
|--------------------|----------------|---------------------------------|-------------|
| collimated, confined| 84 (31)        | 16 (7)                          | 19% (22%)   |
| collimated, eruptive| 30 (17)        | 11 (8)                          | 37% (47%)   |
| loop-like, confined | 87 (43)        | 16 (8)                          | 18% (19%)   |
| loop-like, eruptive | 155 (116)      | 44 (35)                         | 28% (30%)   |
| total              | 356 (208)      | 93 (64)                         | 26% (31%)   |

a Numbers in parenthesis concern well-observed XPEs

observed collimated and eruptive XPEs.

In order to compare morphology and kinematics of the associated XPE-prominence pairs, we organized prominences using the classification scheme developed for XPEs. Table II presents our assignment of particular prominence subclasses applied in the SGD to subclasses defined basing on morphology and kinematics.

Table III summarizes the results of this investigation. Each row presents one subclass of XPEs established by combining both classifying criteria, morphological and kinematical. In the first column, the name of a subclass and the total number of XPEs in the catalogue, for which we found associated prominences, is given. In the next columns the counts of associated prominences are given for particular subclasses separately. These subclasses are defined in the same way as for XPEs (Table II). Moreover, a rate contribution of particular subclasses is written in parenthesis.

The bold-faced numbers situated diagonally in Table III represent the case, in which we conclude the morphological and kinematical similarity between the associated XPE and prominence. As we see, only a minority of events shows this similarity (9-38% for particular subclasses).

To determine influence of which criterium is responsible for the discrepancy between XPEs and prominences, we verified resemblance between the associated XPEs and prominences for each classifying criterion separately. Tables IV and V present the results for the morphological and kinematical criterion, respectively. They are organized in the same way as Table III.
As we can see, 51 from 87 (59%) XPEs, for which we found the associated prominences, is morphologically the same as the prominence. For 36 events (41%) the discrepancy exists: the loop-like XPEs are associated with the collimated prominences or the collimated XPEs are associated with the loop-like prominences.

Considering the kinematical criterion (Table IV) we found resemblance between the associated XPEs and prominences only for 33 from 87 (38%) events. The discrepancy is caused mainly by the eruptive XPEs, for which the majority (78%) of the associated prominences was classified as confined.

### 4. Conclusions and future plans

Our results show that XPEs and prominences are poorer correlated than XPEs and CMEs or prominences and CMEs. Only less than 30% of XPEs is associated with prominences, whereas the correlation in two last cases is about 70%. We found subclasses of XPEs that show higher correlation than
Table III: Resemblance between the associated XPEs and prominences

| XPEs               | Prominences                        |
|--------------------|------------------------------------|
|                    | collimated, confined | collimated, eruptive | loop-like, confined | loop-like, eruptive |
| collimated, confined (16) | 6 (38%) | 2 (12%) | 4 (25%) | 4 (25%) |
| collimated, eruptive (11) | 8 (73%) | 1 (9%) | 2 (18%) | 0 (0%) |
| loop-like, confined (16) | 6 (38%) | 1 (6%) | 5 (31%) | 4 (25%) |
| loop-like, eruptive (44) | 18 (41%) | 1 (2%) | 15 (34%) | 10 (23%) |

the whole population, e.g. collimated and eruptive XPEs, but even in this case the correlation is below 50% (see 2nd row of Table II). We interpret these results as a proof that there is, in the statistical sense, only a modest connection between hot and cool plasma motions in the corona.

Apparent discrepancy of a common occurrence in the triangle: prominences-XPEs-CMEs (Figure 1) can be explained under assumption that the two following subclasses of CMEs exist: (1) associated with prominences and (2) associated with XPEs. Keeping in mind that XPEs show almost 100% correlation with flares, we conclude that our results recall a traditional division of CMEs proposed by Munro et al. (1979). The presence of two separate subclasses of CMEs, that are correlated either with prominences or with flares, is a subject of permanent debate. Although this division is not supported by recent results of kinematical evolution of CMEs (e.g. Vršnak et al., 2005), from the theoretical point of view it is possible that different physical mechanisms responsible for a CME occurrence result in a different level of association with other solar-activity phenomena (Chen, 2011).

Note that the examples in which simultaneous occurrence of an XPE...
Table IV: Morphological resemblance between the associated XPEs and prominences

| XPEs         | Prominences |
|--------------|-------------|
|              | collimated  | loop-like  |
| collimated   | 17 (63%)   | 10 (37%)   |
| loop-like    | 26 (43%)   | 34 (57%)   |

Table V: Kinematical resemblance between the associated XPEs and prominences

| XPEs         | Prominences |
|--------------|-------------|
|              | confined    | eruptive   |
| confined     | 21 (66%)   | 11 (34%)   |
| eruptive     | 43 (78%)   | 12 (22%)   |

and a prominence was found, indicate also that there is only a modest connection between hot and cool plasma motions in the corona, since frequently there is a discrepancy between morphology and kinematics of simultaneously occurring events (Table III).

We could not discuss a relative location of hot and cool plasma ejections because Hα images were unreachable for us. However, under assumption of common vertical expansion of hot and cool plasma, our results suggest the relative location, in which the hot plasma is concentrated higher than the cool plasma (see Table V 43 examples of eruptive XPEs and the confined prominences; 11 examples of confined XPEs and the eruptive prominences).

To make further progress in our investigation, we are going to find counterparts of events from the XPEs catalogue in EUV images obtained by the Transition Region And Corona Explorer (TRACE) satellite. Behavior of warm plasma (1-2 MK), the most typical for the solar corona, should derive additional information concerning interplay between hot and cool plasma. The most interesting, well-observed events will be analyzed separately. Unusual possibilities to make progress in a description of eruptive phenomena in the corona are offered by the new generation of solar orbiting observ-
tories like *Hinode*, *Solar-Terrestrial Relations Observatory (STEREO)*, and the *Solar Dynamics Observatory (SDO)*.

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