Catalog of Solar Failed Eruptions and Other Dynamic Features Registered by SDO/AIA

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Abstract

In this paper we present our attempt to constrain the first catalog of solar failed eruptions. We used our automatic algorithm that is able to search for dynamic features in the Solar Dynamics Observatory (SDO)/Atmospheric Imaging Assembly (AIA) database. We ran the algorithm on the entire SDO/AIA 171 Å data set for the time interval from 2010 May 20 to 2019 May 20 we found 12,192 dynamic events. The dynamic events were classified in three groups. Apart from failed eruptions (1214) we obtained a large group of successful eruptions (2064) and other dynamic events (8914). The automatic algorithm enabled us to collect several observational characteristics, which are provided in files that may be downloaded from the catalog web page. In this paper we present the methodology of catalog preparation and preliminary results of the statistical analysis of observational characteristics obtained by the automatic algorithm.

Unified Astronomy Thesaurus concepts: Solar activity (1475); Solar active regions (1974); Solar filaments (1495); Solar prominences (1519); Solar corona (1483); Solar extreme ultraviolet emission (1493)

1. Introduction

The solar atmosphere is a dynamic environment with different types of moving structures. These structures occur on various time and spatial scales. From terrestrial perspective we are mostly interested in the largest events, which may significantly influence the Earth’s magnetosphere causing various types of threats (Pulkkinen 2007). For this reason coronal mass ejections (CMEs) are intensively investigated (Webb & Howard 2012; Harrison et al. 2018), automatically searched (Robbrecht & Berghmans 2004; Morgan et al. 2012; Hess & Colaninno 2017; Patel et al. 2018), cataloged (see links and references in Richardson et al. 2015), and reasonably predicted (Song et al. 2006; Qahwaji et al. 2008; Hess & Zhang 2015; Kay et al. 2017; Kay & Gopalswamy 2018). However, the relationship between strong solar flares and CME occurrence is weak and there are many exceptions that do not follow a strong flare–strong CME pattern. Even the strongest, X-class flares may not be accompanied by CMEs (Wang & Zhang 2007). Apart from individual events the Sun can surprise us with huge active regions producing dozens of M- and X-class flares, which are completely CME-less (Chen et al. 2015; Sun et al. 2015). This suggests that we do not know all or at least key physical conditions in whole active regions as well as in individual flares, which determine whether a certain magnetic field reconfiguration will eventually result in a CME occurrence or not. Therefore, we need to investigate in details events that do not develop into CMEs, even if their properties (i.e., magnetic field complexity, power of a flare, etc.) favor the appearance of such.

Two types of events should be investigated from this point of view. The first are confined flares (Schmahl et al. 1990), which do not produce a CME and are not accompanied by any dynamic structures. The second are failed eruptions (Ji et al. 2003), which are a type of dynamic structure that are abruptly stopped in the solar corona after initial acceleration and upward movement. Gilbert et al. (2007) defined the failed eruption as an eruption for which neither magnetic field nor matter escapes the Sun thus no CME is observed. Sometimes, these two types of events are mixed because a flare without a CME but accompanied with a failed eruption can be still classified as a confined flare. However, generally speaking, not every confined flare is connected with a failed eruption and vice versa.

We decided to concentrate on failed eruptions because they start as typical eruptions that should eventually develop into a CME but do not for unclear reasons. The statistical analysis of a large group of failed eruptions should refine boundary conditions for CME occurrence. There are several scenarios that may explain the confinement of the eruption: too strong tethers (Vršnak 1990), dynamic magnetic tension force in an erupting structure (Myers et al. 2015), flux emergence complexity (Archontis et al. 2007), kink instability leading to a stable configuration of an erupting flux tube (Török et al. 2004), reconnection with a magnetic field overlying the eruption site (Amari & Luciani 1999), and others.

From the observational point of view, before the Solar Dynamics Observatory (SDO)/Atmospheric Imaging Assembly (AIA; Lemen et al. 2012), failed eruptions were observed and analyzed only occasionally. One of the most often analyzed events is a failed eruption that occurred on 2002 May 27 (Ji et al. 2003). This is an example of an eruption stopped by a kink of a magnetic flux rope. During the eruption braking of the reconnection inside the eruption took place (Alexander et al. 2006). Additionally the overlying field decreased slowly with height, which was found to be an important factor leading to the eruption confinement (Török et al. 2004). In recent years an overlying magnetic field decay index became the most investigated observational feature connected with failed eruptions and/or confined flares (Moore et al. 2001; Liu 2008; Guo et al. 2010; Baumgartner et al. 2018).

Failed eruptions may also interact with an overlying magnetic field. This interaction leads to an occurrence of rare type oscillations (Mrozek 2011) or the reconnection with the overlying field (Amari & Luciani 1999). The signs of electrons accelerated due to such an interaction were analyzed in three cases of failed eruptions by Netzel et al. (2012). The authors
found one example of a hard X-ray (HXR) source produced by electrons accelerated during the failed eruption interaction with overlying fields. We expect that such weak sources should be more frequently observed by more sensitive future instruments like the Spectrometer/Telescope for Imaging X-rays (Krucker et al. 2013), which will observe the Sun from a short distance. The overlying magnetic field role in flare confinement was also discussed by Wang & Zhang (2007). In their work the other parameter was investigated, i.e., the location of the flare in an active region. The authors found that flares are more pronounced to be eruptive if located closer to the edge of an active region, while confined events were located closer to the center.

The existing analyzed samples of failed eruptions are usually small. In most of published papers the results are presented for one carefully selected event (e.g., Ji et al. 2003; Kumar et al. 2011; Mrozek 2011; Chen et al. 2013; Song et al. 2014; Kushwaha et al. 2015; Hassanin & Kliem 2016; Li et al. 2018; Song et al. 2018). From this point of view it is impossible to investigate statistically processes that lead to eruption confinement. The main reason is that the database of SDO/AIA observations is huge, and automatic search for events of a given type is slow and uncertain. Until now only one algorithm for an automatic search for solar eruptions in SDO/AIA database has been constructed (Hurlburt 2015). In this method the authors search for optical flows based on the Fourier analysis restricted to the first few elements. Therefore, the algorithm is optimized to search for large structures. The results were compared with the Heliophysics Events Knowledgebase (HEK; Hurlburt et al. (2012)). The comparison showed that the algorithm is far more effective than a human. The HEK database contains 75% fewer entries than the automatic algorithm. The authors explain this result as a product of moments of inattention or subjective selection of events—not all are considered as interesting by a human. The authors showed that a human has less sensitivity for fast, short-lived eruptions while the automatic algorithm performs worse for non-slow, long-evolving eruptions. It has to be mentioned that the algorithm searched for all types of eruptions and was unable to automatically detect failed ones.

In this paper we present our attempt to constrain the first catalog of failed eruptions. We used the automatic algorithm that is able to search for dynamic features in the SDO/AIA database. Next the found dynamic events were classified in a few groups. One of them contains failed eruptions for which we determined several observational characteristics. All the events are collected in the online catalog.

2. Observational Data

The SDO (Pesnell et al. 2012) was launched on 2010 February 11. It carries three experiments. One of them is the AIA (Lemen et al. 2012) dedicated to image the entire solar disk with the use of several wide-band filters. AIA consists of a set of four 20 cm, normal incidence telescopes. Their 41′ field of view is covered with 4096 × 4096 charge-coupled devices (CCDs), giving the angular resolution of 1.5″. Images are taken in 10 bands (including 7 extreme ultraviolet (EUV) bands) with 12 s time resolution. Therefore the amount of data produced by the instrument is enormous: 1.5 TB per day. It is impossible to run an automatic algorithm that downloads and analyzes original full-resolution data in a reasonable time. For this reason we decided to use images reformatted to the synoptic 1.5 level that are the full-disk images compressed to 1024 × 1024. The time cadence of synoptic 1.5 level data is 2 minutes. Such data provide time and spatial resolutions that are very suitable for searching different types of moving structures.

We restricted our search to the 171 Å band. However, the developed algorithm may be easily adopted for other bands and other instruments. The characteristic of AIA 171 filter is suitable for searching hot (above 10⁶ MK) as well as cold (around 3 × 10⁵ K) plasma structures. It was important to have both hot and cold components mixed because the erupting plasma may be heated or cooled and become invisible in filters responding for cold or hot plasma only.

Downloading and processing of the data was performed automatically. We decided to perform our search on data packets covering 3 hr of observations. The data packets had 15 minutes overlap to reduce edge effects. This overlap worked well for short events, but longer ones were often divided into two when occurred on the border between two data packets. Every not a number (NaN) pixel was replaced with the use of IDL’s CONVOL function. The last step of data cube preparation was blurring of each image with a Gaussian filter (FWHM = 2.8).

3. Automated Search for Dynamic Events

Each 3 hr long data packet searched for eruptive pixels according to the algorithm described in Mrozek et al. (2016). We used Bayes approach to classify pixels into two groups: eruptive and quiet pixels. The search was performed on various areas with different sizes and shapes. This strategy slowed the algorithm but allowed us to find large as well as small eruptions. Complexes of eruptive pixels found were classified as a dynamic structure if several conditions were fulfilled.

1. Each pixel had a probability of being eruptive greater than 0.35.
2. The structure was visible on eight or more consecutive frames.
3. The area covered by the eruptive pixels complex was greater than 600 arcsec² on at least one frame.
4. The structure mean brightness was above 30 digital number (DN) on at least one frame.
5. The structure revealed the change of centroid position greater than 25″.

The algorithm is moderately effective in searching for dynamic events in large data sets (Mrozek et al. 2016). However, it performs searches in a reasonable time. The search performance depended on the solar activity level. The analysis of one month of SDO/AIA observations lasted from 3 to 10 days. We run the algorithm on up to three personal computers, which means that the search of the whole 171 Å image database finished in 10 months.

Apart from eruptions, the algorithm is very sensitive to motions of faint plasma structures in the solar atmosphere like expansion, untwisting, oscillations, and globally propagating waves in the solar corona (commonly called “EIT waves”). In the case of large eruptions, when even the entire solar disk is disturbed, the algorithm could find an eruption and a variety of small disturbances that were related to the eruption. Therefore, the number of small events may be overestimated and should be interpreted with care.

When a dynamic event was detected the algorithm produced two types of outputs. The first is a three-panel plot. An example
is presented in Figure 1. It contains a 171 Å image, the same image with overlay contour presenting the eruptive pixels complex, and the differential image. The second output is an External Data Representation format file containing a structure with various parameters obtained by an automated algorithm for a given dynamic event. Table A1 (in the Appendix) contains the description of each field in the structure.

We ran the algorithm on the entire SDO/AIA data set. For the time interval from 2010 May 20 to 2019 May 20 we found 12,192 dynamic events. The distribution of events on the solar disk is presented (see Figure 2, left panel). They are concentrated along active latitudes, but there is a significant fraction of events located closer to the poles. The right panel of Figure 2 presents the dynamic events’ occurrence in 120 day long bins. Two maxima are visible around the years 2012 and 2015. These are time correlated with the distribution of the Wolf numbers during the 24th cycle presented with the dotted line.

4. Classification of the Events

The solar atmosphere is full of various types of static and dynamic structures. A large number of various classification schemes exists depending on the wavelength, morphology, kinematics, spectroscopy, spatial scale, etc. (e.g., Tomczak & Chmielewska 2012; Zhang et al. 2012; Freed & Russell 2014; Nicewicz & Michalek 2016; Barnes et al. 2017; Paraschiv & Donea 2019). We concentrate on moving structures therefore we refer to Gilbert et al. (2007) who classified eruptions depending on their ability to escape from the Sun. Namely they divided eruptions into three types: full, partial, and failed. The first is a type of an eruption in which the entire (more than 90%) magnetic structure and/or plasma escapes from the Sun. The partial eruptions are further divided into: the “type a” when the entire magnetic structure erupts with a small amount or without plasma, and the “type b” for a partial eruption of the magnetic structure with a small amount or without plasma. The third type is a failed eruption whose magnetic structure filled
with plasma, after initial acceleration, stops in the low corona. These eruptions may be related to a CME occurrence. The full and partial eruptions are related to CMEs, while the failed eruptions do not produce CMEs. This kind of an eruption–CME relation is sometimes confused with another classification which raised from the flare–CME relation (Pallavicini et al. 1977) who divided flares into two groups: flares accompanied by CMEs (eruptive) and not accompanied (failed).

We merge the existing classification of flares and eruptions by collecting them into one diagram presented in the the Figure 3. We extended the eruption classification of Gilbert et al. (2007) with one additional type of eruption. These are confined jets (Wyper et al. 2016) which may be treated as a type of a failed eruption in which plasma motion is observed without visible dynamics of the magnetic structure. Namely we observe only plasma moving along the magnetic structure. This is a type of an event that is similar to a surge in Hα observations (Engvold 2015). The internal tiles in Figure 3 refer to eruptive and confined flares. An eruptive flare may be accompanied by a full or a partial eruption, but there is also possible that the full or the partial eruption occurs without a flare. That is the reason why the tiles representing full and partial eruptions are slightly larger than the flare tiles. A similar situation is for confined flares that may be accompanied by a failed eruption or a confined jet. However, there are failed eruptions and confined jets which occur without visible flares.

The confined jets have been excluded from the failed eruptions group as they may represent physically a different group. Vršnak (2019) analyzed the analytical flux tube model to investigate the pre-eruptive phase of solar eruptions. The author distinguished three processes leading to the eruption: twisting motions of the flux-rope foot points, emergence of a new magnetic flux beneath the flux rope, and a mass leakage down the flux-rope legs. In our morphological classification the first refers to confined jets, and the second to failed eruptions. We do not take into consideration the mass draining since it may occur in any type of an eruption. However, apart from a naming convention, we treat failed eruptions and confined jets as eruptions that do not escape from the Sun. Therefore, in the catalog, they both are collected in one group named “failed eruptions,” but for confined jets we include information in a “comments” file.

5. Catalog Content

The classification of the dynamic events has been done by a human. We decided to divide the dynamic events into three groups.

1. Small/unclassified events: includes all small-scale mass movements, post-flare loops, flares, oscillating loops, mass draining after successful eruptions, prominences, etc.
2. Successful eruptions: contains full and partial eruptions. Each event from this group can be related to a CME from the SOlar and Heliospheric Observatory (SOHO)/Large Angle Spectrometer CORonagraph (LASCO) CME catalog.5
3. Failed eruptions: both failed eruptions and confined jets are included in this class. We restricted the number of confined jets to events associated with flares.

The present version of the catalog5 contains data for the time period from 2010 May 20 to 2019 May 20; this version is archived in the RepOD repository at [doi:10.18150/F0BC6C] under a CC0 Creative Commons Zero 1.0 license. There are two types of catalog entries. The first is dedicated to small/unclassified and successful eruptions. We provide the information for them obtained from automatic algorithm results only. It means that there is a plot containing location of an event, a time history of centroid location, intensity, and an area of the eruptive pixels complex. Additionally we include a movie showing animations of triple panels (an example of a single frame is presented in Figure 1) and a file with all parameters estimated by the automatic algorithm. A description of the parameters is presented in Table A1 (in the Appendix).

The more comprehensive catalog entry is dedicated to failed eruptions only. Here we provide more detailed information concerning kinematics. Using automatic algorithm results we calculate a position of an eruption front. The obtained time evolution of the altitude of the eruption front is spline smoothed and its first (velocity), and second (acceleration) derivatives are calculated. Additionally, for each failed eruption, we estimate the eruption front position manually, and derive kinematic parameters as well. The results obtained are presented on estimated height and velocity plots. Moreover, we include the RHESSI quick look plot for HXRs in the following energy channels: 6–12, 12–25, 25–50, 50–100, and 100–300 keV. The maximum values of speed, deceleration, and altitude are also presented in the catalog entry. For more details, please refer to the help page of the catalog.6

6. Observational Characteristics of the Events

Among the dynamic events we have classified 1214 failed eruptions, 2064 successful eruptions, and 8914 small/unclassified events. In Figure 4 we present histograms of some observational characteristics estimated with our automatic algorithm.

1. Direction—an angle between the eruption front direction and the radial direction.
2. Duration—a time span of a dynamic feature defined by parameters described in Section 3.
3. Latitude—the heliocentric Y coordinate of a dynamic feature.

4 http://eruptivesun.com/help
5 http://eruptivesun.com
6 http://eruptivesun.com/help

Figure 3. The Euler diagram of existing naming conventions related to flares and eruptions.

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It has to be mentioned that the small/unclassified group is not uniform. For example, when a large eruption occurred, disturbing almost the entire visible corona, then the automatic algorithm found dozens small dynamic features like side eruptions, oscillations, waves, etc., connected with this large eruption. Moreover, this group contains false positives, which are brightenings without any dynamic behavior. We counted such events for the period of 2012 April 1–2013 April 1. Thus, we may expect that around 4% of small/unclassified events are false positives, which is less than 3% of all events found by the algorithm. Nevertheless, we do present the results for small/unclassified events for completeness.
The first row in Figure 4 presents directions of eruptions with regard to the radial direction. It can be seen that the successful eruptions are mainly ejected in the radial direction. They are concentrated around direction 0°. Directions of the failed eruptions and the confined jets are spread between 0° and 90°. We expect that this is mainly connected with more numerous weak eruptions, and inclusion of the confined jets which move along magnetic field lines. Directions of the small/unclassified events are even more spread with the maximum visible around 70°. We expect that such an effect is caused mainly by geometrical effects since we have relatively many events close to the solar limbs.

The second row in Figure 4 presents durations of the detected events. About 30% of the small/unclassified events are concentrated in the interval 20–30 minutes. We may expect a power-law distribution of the durations of small events. Thus, majority of them will occupy the shortest times of the histogram that can be detected by our algorithm. The algorithm was defined to search for events that last at least 16 minutes (eight images taken with a 2 minute cadence), which is quite long for small events. The successful eruptions have the second maximum around a value of 160 minutes. It means that the 3 hr long data packets that we analyzed are too short for some events. We expect that they could be detected in two separate data packets as two separate events. This may produce some bias in data interpretation, but they are less than 7% of all successful eruptions. Distribution of the duration of the failed eruptions and the confined jets is wider than for the small/unclassified events and slightly narrower than for the successful eruptions. It can be seen that above 100 minutes the population of events is stable in each time bin, and there is no maximum around 160 minutes. This suggests that the assumed 3 hr long time window for the analyzed data packets was chosen well and allows us to detect the majority of the failed eruptions as single events without splitting them into two.

The last row in Figure 4 presents the heliocentric Y coordinate of detected dynamic events. All three types are concentrated mainly in active latitudes. Each histogram has a slight asymmetry when comparing both solar hemispheres. Namely we detected more events in the Northern Hemisphere (positive values of Y) than in the Southern one. Moreover, we noticed that the failed eruptions and the confined jets are slightly more concentrated toward the equator than the successful eruptions. The interpretation of this effect is outside the scope of this paper and will be analyzed in further work.

7. Summary

In this paper we present the first catalog of failed eruptions. We used our automatic algorithm that is able to search for dynamic features in the SDO/AIA database. Additionally, as a side effect we obtained a large group of successful eruptions and other dynamic events that we decided to include in the catalog. The dynamic events were classified in three groups: the small/unclassified, the successful eruptions, and the failed eruptions (merged into one group with the confined jets). The automatic algorithm enabled us to collect several observational characteristics which are provided in files that may be downloaded from the catalog website. Apart from the parameters provided by the automatic algorithm we determined more kinematic characteristics for the failed eruptions and the confined jets. All events are collected in the online catalog.

We analyzed several observational characteristics obtained by the automatic algorithm. We found that the successful eruptions are mostly radial eruptions. The failed eruptions and the confined jets show more diverse directions. The histograms containing durations of the small/unclassified and the successful eruptions show some data selection effects. Namely we assumed that events lasting less than 16 minutes or more than 180 minutes are not taken into consideration. The correctness of such an assumption is confirmed by the histogram of durations of the failed eruptions and the confined jets that show almost no data selection effects. The last of the presented parameters is a heliocentric Y coordinate. We detected here some asymmetry between the hemispheres for each of the defined groups. Moreover, we observed that the failed eruptions are more concentrated around equator than successful eruptions.

In this paper we present only the catalog and the general results from the automatic algorithm. Each group of events in our catalog is not homogeneous. Thus, a more sophisticated analysis based on our crude classification of events (small/unclassified/successful/failed) is not possible. Even the subgroup of failed eruptions (after exclusion of confined jets), on which we focus our attention, cannot be considered homogeneous. As mentioned in Section 1, there are several possible mechanisms, which may be involved in confinement of an eruption. Therefore, a deep analysis of failed eruptions, including their kinematics, energetics, and relation to overlying magnetic fields, needs a proper selection of events first and then their careful examination. Such an analysis will be presented in our subsequent paper.

All events are presented in the online catalog, and may be freely downloaded and analyzed. This is the first such a collection of failed eruptions and confined jets. Apart from them we provide data for successful and small/unclassified events. We hope that this kind of collection may be useful for training the artificial intelligence algorithms to improve their ability in finding events of a given type. We will perform such a test of a new algorithm in the near future.

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Appendix

Table A1 presents description of data fields in the structure that is generated by our automated algorithm. The structure contains parameters estimated automatically for dynamic events found by the algorithm. A file with the structure for each event is available in our catalog and can be downloaded by the user.
### Table A1
Dynamic Events Parameters

| Field Name      | Data Type | Units       | Description                                                                 |
|-----------------|-----------|-------------|------------------------------------------------------------------------------|
| ID              | LONG      |             | Not used                                                                     |
| T_START         | DOUBLE    | seconds     | Event start time                                                             |
| T_END           | DOUBLE    | seconds     | Event end time                                                               |
| T_PEAK          | DOUBLE    | seconds     | Time of maximum area of eruption                                              |
| DURATION        | FLOAT     | seconds     | Event duration                                                               |
| WAVE            | LONG      | Å           | SDO/AIA filter in which an event has been detected                           |
| N_POINTS        | LONG      |             | Number of frames covering the entire event                                   |
| TIMES           | DOUBLE[80]| seconds     | Times of images registration                                                  |
| AREA_X          | FLOAT[80]| arcsec²     | Mean of the differential image in the eruption area                           |
| AREA_M          | FLOAT[80]| arcsec²     | Eruption area maximum                                                         |
| INTENS          | FLOAT[80]| DN          | Mean intensity in the eruption area                                           |
| INTENS_X        | FLOAT[80]| DN          | Maximum of the mean intensity in the eruption area                            |
| DIFF_T          | FLOAT[80]| DN          | Mean of the differential image in the eruption area                           |
| N_DIFF_T        | FLOAT[80]|            | Mean of the normalized differential image in the eruption area               |
| F_VAR           | FLOAT[80]|            | Mean value of the variability index during the entire event                  |
| F_VAR_M         | FLOAT[80]|            | Mean value of the variability index during the entire event                  |
| NOTHING         | INT       |             | Not used                                                                     |

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