

LETTER TO THE EDITOR

Topological ignition of the stealth coronal mass ejections

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ABSTRACT

Context. One of hot topics in the solar physics are the so-called ‘stealth’ coronal mass ejections (CME), which are not associated with any appreciable energy release events in the lower corona, such as the solar flares. It is sometimes assumed that these phenomena might be produced by some specific physical mechanism, but no particular suggestions were put forward.

Aims. It is the aim of the present paper to show that a promising explanation of the stealth CMEs can be based on the so-called ‘topological’ ignition of the magnetic reconnection.

Methods. As a theoretical basis, we employ the Gorbachev–Kel’ner–Somov–Shvarts (GKSS) model of formation of the magnetic null point, which is produced by a specific superposition of the remote sources (sunspots) rather than by the local current systems.

Results. As follows from our numerical simulations, the topological model explains very well all basic features of the stealth CMEs: (i) the plasma eruption develops without an appreciable heat release from the spot of reconnection, *i.e.*, without the solar flare; (ii) the spot of reconnection (magnetic null point) can be formed far away from the location of the magnetic field sources; (iii) the trajectories of eruption are strongly curved, which can explain observability of CMEs generated behind the solar limb.

Conclusions. Therefore, the topological ignition of magnetic reconnection should be interesting both by itself, as a novel physical phenomenon, and as a prognostic tool for forecasting the stealth CMEs and the resulting unexpected geomagnetic storms.

Key words. Sun: coronal mass ejections (CMEs) – Sun: activity – Magnetic reconnection – Methods: analytical – Methods: numerical

1. Introduction

Since the discovery of the coronal mass ejections (CME) in the early 1970’s (*e.g.*, review Howard 2006, and references therein), it was known that in some cases they could be reliably associated with other manifestations of the solar activity in the lower corona (first of all, the solar flares); while in other cases it was impossible to trace such a relationship (Chen 2011; Webb & Howard 2012; Howard & Harrison 2013; Nitta et al. 2021; Reva et al. 2024). However, the undetectable origin of the respective CMEs was attributed for a long time just to the insufficient quality of observations.

Meanwhile, in the course of development of the observational technique it was gradually recognized that the initiation of some CMEs might be inherently unobservable. As a result, the term ‘stealth CME’ emerged and became widely used in the last decade. Unfortunately, the nature of this phenomena remains unclear till now. One point of view is that there is a continuous spectrum of CMEs with various expression of energy release in the lower corona; and the stealth CMEs belong just to one of the wings of this spectrum. Another point of view is that there should be a special mechanism for the production of such CMEs, but its physical principles are still unknown.

It is the aim of the present Letter to show that a promising candidate for the above-mentioned mechanism is the so-called ‘topological’ ignition (or trigger) of the magnetic reconnection, whose general principles were formulated quite a long time ago by Gorbachev et al. (1988) but remained poorly exploited till now. Here, we shall perform the detailed numerical simulations

of the respective process and show that its basic features are in perfect agreement with the observed properties of the stealth CMEs.

2. Theoretical model and simulations

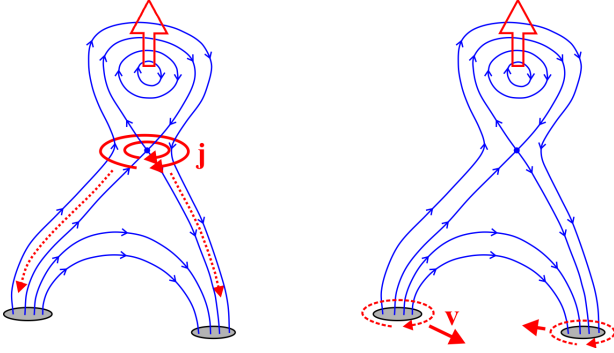
It is commonly believed that the main source of the solar activity is the magnetic reconnection, when the magnetic field lines break apart and then connect again in a new configuration (*e.g.*, monographs Priest & Forbes 2000; Somov 2013). This process takes place in the so-called null (or neutral) points, where all components of the magnetic field vanish (Parnell et al. 1996; Dumin & Somov 2016). Such a null point is usually assumed to be formed by the *local current systems*; this corresponds to the ‘standard’ scenario of magnetic reconnection. On the other hand, there is yet another option for the appearance of the null point, which is often overlooked. This is a specific superposition of influences by the *distant sources*, which can result in the X-type configuration with vanishing magnetic field in its center. The possibility of such superposition was proved for the first time by Gorbachev et al. (1988) by utilizing rather sophisticated theorems of differential geometry and algebraic topology, and the respective effect was called the ‘topological trigger’ of magnetic reconnection. The most important differences between the ‘standard’ and ‘topological’ scenarios are summarized in Table 1.

Our consideration will be based on the above-mentioned Gorbachev–Kel’ner–Somov–Shvarts (GKSS) model, whose specific feature is the existence of the specific ‘topologically unstable’ arrangements of the magnetic-field sources (sunspots). Their tiny variation results in the dramatic reconstruction of the

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Table 1. Basic features of the ‘standard’ and ‘topological’ mechanisms of the magnetic reconnection.

	Standard reconnection	Topological reconnection
1. Source of the magnetic field	Local electric currents	Superposition of the remote sources
2. Geometrical structure of the reconnecting region	Determined by the local magnetic field lines	Determined by the global configuration of the magnetic field
3. Speed of propagation of the reconnection in space	Limited by the Alfvénic velocity	Irrelevant to the Alfvénic velocity
4. Heat release in the spot of reconnection	Substantial	Insignificant

**Fig. 1.** Sketch of development of the magnetic reconnection in the standard (left panel) vs. the topological (right panel) scenarios.

magnetic field in the entire space; and just this effect will be substantially employed below (for a particular example of the unstable configuration, see Fig. 2 in Dumin & Somov 2024).

A few topological models of another type were developed in late 1990’s and early 2000’s by the group of E.R. Priest (for example, Brown & Priest 1999; Invernizzi & Priest 1999; Brown & Priest 2001). They assumed a rather regular arrangement of the sources in the photospheric plane and then considered the emergence of a new null point as a result of its ‘squashing’ out of this plane, when the above-mentioned sources converged. Unfortunately, eruption of the null point in such models turns out to be rather slow (of the same order as velocity of the sources); and, therefore, they are less appropriate for the description of CMEs. (For application of the topological methods to various solar phenomena, see review Longcope 2005, and references therein.)

The first—and most important—reason why the topological models look very promising for the description of stealth CMEs is illustrated in Fig. 1: In the ‘standard’ scenario, development of the magnetic reconnection leads both to a heat release due to the dissipation of the local current system \mathbf{j} (resulting in the solar flare) and a detachment of the plasma bunch from the null point (the CME eruption). On the other hand, in the ‘topological’ scenario, the reconnection is caused by the motions \mathbf{v} of the photospheric sources, without any currents immediately at the spot of reconnection. This results solely in the CME eruption.

Moreover, apart from the above-mentioned ‘energetic’ argument, there are two additional ‘geometric’ arguments in favor of the topological mechanism as explanation of the stealth CMEs. They follow from the simulations presented in Fig. 2. The magnetic field was assumed to be formed by the two pairs of the point-like sources of equal magnitude but opposite signs located in the plane of photosphere or somewhat below it. From the physical point of view, they represent open ends of the magnetic-flux tubes originating in the deeper layers of the Sun (for addi-

tional discussion, see the introductory section in Zhuzhoma et al. 2022). The global magnetic field in this situation is described by the so-called ‘two-dome structure’, which separates the entire space into the four topologically distinct subregions (e.g., Fig. 3 in Somov 2008). Some further mathematical details for the simulations can be found in Appendix A of paper by Dumin & Somov (2019) and Appendix A of the present paper.

As was predicted in the pioneering work by Gorbachev et al. (1988), there are specific ‘topologically unstable’ arrangements of the magnetic sources, when a tiny shift of one of them results in a dramatic reconstruction of the entire magnetic field. The most studied configuration of the unstable type is formed when the sources are located approximately in the vertices of the slanted letter ‘T’, as illustrated below in Fig. 4; see also right panel of Fig. 2 in paper by Dumin & Somov (2024). So, if the unstable configuration is realized, the above-mentioned two-dome structure experiences a sudden flipping, as is seen in the left panels of Fig. 2 and, especially, in Supplementary movies. To avoid cluttering the pictures with unnecessary details, we represent only the ‘topological skeletons’, which are the sets of magnetic-field lines connecting the sources and null points; two different colors (red and blue) refer to the field lines emanating from the sources of two different polarities.

Next, which is the most important, the above-mentioned flipping leads to the emergence and fast motion of a new null point high above the plane of the sources, as shown by the yellow curves. Therefore, a magnetic reconnection—unrelated to any local currents—should develop along this trajectory; and a plasma blob can detach and escape away somewhere in the end of this curve. Just this effect might be a reasonable explanation for the formation of the stealth CMEs, since it is not associated with any heat release.

One can also see in the simulations two important geometrical properties of the null-point trajectories:

1. They are strongly bended. Therefore, even if such an eruption occurred on the back side of the Sun, it might be well observable from the Earth, as illustrated in Fig. 3.
2. Directions of the outbursts are crucially dependent on the particular type of motion of the sources in the region of topological instability. Namely, if the central source is shifted to the right, the eruption originates somewhere inside the source region and is directed outwards (two upper panels in Fig. 2). On the other hand, if the central source is shifted (almost from the same position) to the left, then the eruption originates quite far away from the source region and is directed towards this region. Such a behavior is illustrated more pictorially in Fig. 4. Therefore, approximately in 50% of cases the eruption looks ‘detached’ from the sources (i.e., the active region on the Sun).

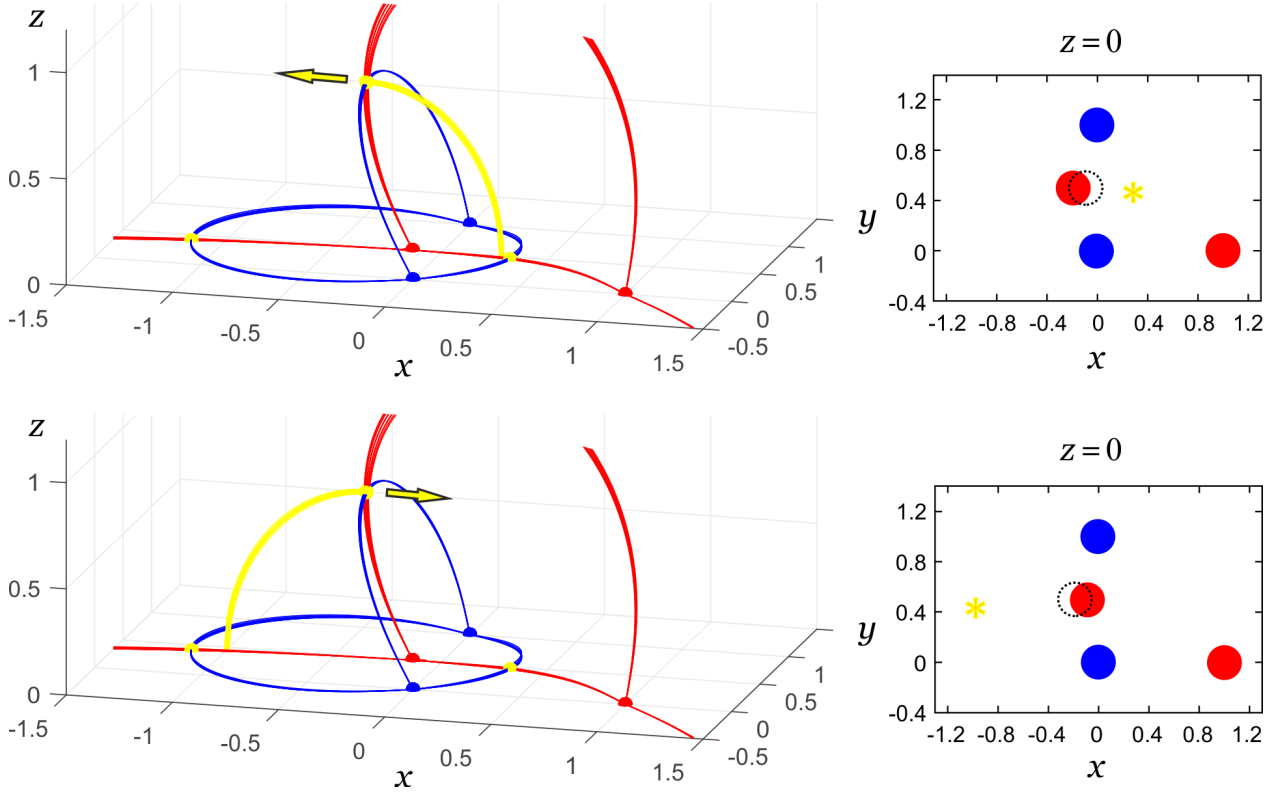


Fig. 2. Left panels: magnetic skeletons (red and blue curves) and trajectories of eruption of the null points (yellow curves) in the region of topological instability. Right panels: respective arrangements of the magnetic sources in the plane of photosphere before (solid circles) and after (dotted circles) development of the instability. The spots of emergence of the null points (*i.e.*, onset of the eruption) are designated by the yellow stars.

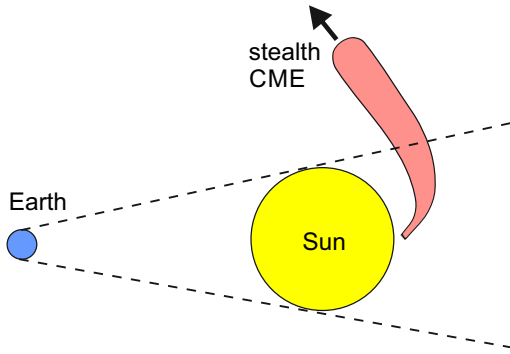


Fig. 3. Sketch of the strongly-bended trajectory of CME, facilitating its observation from the Earth.

3. Discussion

As follows from the above consideration, there are three strong arguments—one energetic and two geometrical—why the topological mechanism is a promising explanation of the stealth CMEs; and the observational findings are well in agreement with our simulations.

Really, as was mentioned by Nitta et al. (2021), the stealth CMEs are faint and slow, which assumes that they involve less energy than normal CMEs. However, this feature was attributed by the above-cited authors just to the empirical fact that the magnetic energy available for an eruption above a quiet-Sun or decayed active region should be substantially less than the energy

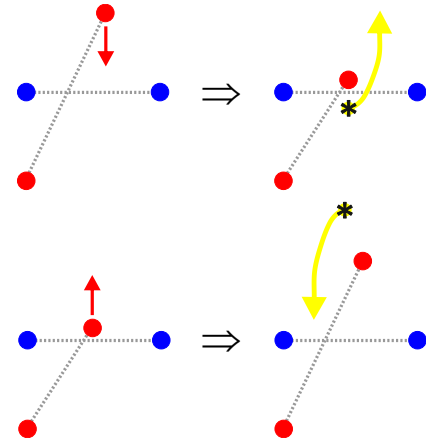


Fig. 4. Two types of eruption of the null point: (top panel) the outward eruption, when X-type configuration transforms into the T-type one; and (bottom panel) the inward eruption, when T-type configuration transforms into the X-type one. Blue and red circles are the point-like magnetic sources of opposite signs, and the straight arrows show the directions of their motion. Yellow curves with arrows designate trajectories of the null points, and the spots of their origin are marked by black stars. The dashed grey lines are drawn just for the visual aid. (These pictures are rotated by 90° with respect to the right panels in Fig. 2.)

from a volume above a strong-field active region. On the other hand, the topological model suggests a much more profound basis for explanation of the low energy.

Besides, as emphasized by Howard & Harrison (2013), “CMEs themselves can erupt with an invisible or almost invisible signature in coronagraphs as well”, because they may be just the “erupting magnetic structures” and “take place without containing sufficient excess plasma.” In fact, just this property is postulated in the formulation of the topological models.

Next, the first geometric feature—namely, a strongly-curved trajectory of ejection—can answer the question posed, *e.g.* by Robbrecht et al. (2009): how can a CME originating on the back side of Sun have any geoeffective action? The second geometric feature—an apparent ‘detachment’ of the spot of eruption from the region of magnetic sources, which is realized in about half of the cases—can explain the so-called ‘random’ coincidences of the CMEs with the strong flares in the opposite quadrant of the solar disk (*e.g.*, Fig. 3(d) in paper Reva et al. 2024).

Finally, let us mention that over a decade ago Oreshina et al. (2012) already speculated that a formation of CMEs could be caused by the topological instability (or ‘topological trigger’) of the coronal magnetic fields, but they discussed only the CMEs associated with solar flares. Unfortunately, it was overlooked that even a more promising scope of applicability of the topological models might be just the stealth CMEs.

4. Conclusions

The topological models of magnetic reconnection were suggested over 35 years ago but were repeatedly criticized since that time for their inability to explain an appreciable heat release due to the reconnection. However, this disadvantage transforms into the crucial advantage when it is necessary to interpret the stealth coronal mass ejections, occurring without the solar flares. Really, the topological mechanism can easily explain a global reconstruction of the magnetic field without any heat release in the vicinity of the null point responsible for the reconnection. Moreover, the geometrical properties of eruptions characteristic of the topological models (namely, their strongly curved trajectories and a ‘detachment’ of the spot of eruption from the source region) are also very favorable for explanation of the stealth CMEs.

At last, it is important to emphasize that the topological models do not require to introduce any kind of the ‘new physics’. In fact, they are based just on the thorough analysis of the specific magnetic-field configurations on the basis of Maxwell equations, which are even simpler than the standard MHD.

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References

- Brown, D. S. & Priest, E. R. 1999, *Sol. Phys.*, 190, 25
 Brown, D. S. & Priest, E. R. 2001, *A&A*, 367, 339
 Chen, P. F. 2011, *Living Rev. Solar Phys.*, 8, 1
 Dumin, Yu. V. & Somov, B. V. 2016, *Ast. Lett.*, 42, 774
 Dumin, Yu. V. & Somov, B. V. 2019, *A&A*, 623, L4
 Dumin, Yu. V. & Somov, B. V. 2024, *MNRAS*, 528, L15
 Gorbachev, V. S., Kel’ner, S. R., Somov, B. V., & Shvarts, A. S. 1988, *Soviet Ast.*, 32, 308
 Howard, R. A. 2006, in N. Gopalswamy, R. Mewaldt, & J. Torsti (eds.), *Solar Eruptions and Energetic Particles*, Geophys. Monogr. Ser., Vol. 165, p 7 (Amer. Geophys. Union)
 Howard, T. A. & Harrison, R. A. 2013, *Sol. Phys.*, 285, 269
 Invernarity, G. W. & Priest, E. R. 1999, *Sol. Phys.*, 186, 99

- Longcope, D. W. 2005, *Liv. Rev. Sol. Phys.*, 2, 7
 Nitta, N. V., Mulligan, T., Kilpua, E. K. J., et al. 2021, *Space Sci. Rev.*, 217, 82
 Oreshina, A. V., Oreshina, I. V., & Somov, B. V. 2012, *A&A*, 538, A138
 Parnell, C. E., Smith, J.M., Neukirch, T., & Priest, E. R. 1996, *Phys. Plasmas*, 3, 759
 Priest, E. & Forbes, T. 2000, *Magnetic Reconnection: MHD Theory and Applications* (Cambridge Univ. Press, Cambridge, UK)
 Reva, A., Loboda, I., Bogachev, S., & Kirichenko, A. 2024, *Sol. Phys.*, 299, 55
 Robbrecht, E., Patsourakos, S., & Vourlidas, A. 2009, *ApJ*, 701, 283
 Somov, B. V. 2008, *Ast. Lett.*, 34, 635
 Somov, B. V. 2013, *Plasma Astrophysics, Part II: Reconnection and Flares* (2nd ed., Springer, NY)
 Webb, D. F. & Howard, T. A. 2012, *Living Rev. Solar Phys.*, 9, 3
 Zhuzhoma, E. V., Medvedev, V. S., Dumin, Yu. V., & Somov, B. V. 2022, *Physica D*, 436, 133320

Appendix A: Basic mathematical formalism

Analysis in the framework of GKSS model is usually performed in two steps: First of all, structure of the magnetic field \mathbf{B} is calculated in the magnetostatic approximation:

$$\mathbf{B} = -\nabla\Phi, \quad \Delta\Phi = 0, \quad (\text{A.1})$$

where Φ is the scalar magnetic potential. So, the time enters into the solution only as a parameter, due to the temporal dependence of the magnetic sources (which are usually assumed to be located at the boundary of the volume under consideration, *e.g.*, at the level of photosphere or somewhat below it). Next, the plasma motion and the associated processes (heating, emission, *etc.*) are analyzed in the given magnetic field.

A key point in the construction of topological model is searching for the specific ‘topologically unstable’ arrangement of the sources, where their small variation results in the emergence of a new null point and its subsequent fast eruption out of the plane of the sources. As seen in the simulations presented in Section 2, this process is associated with sharp reconstruction of the magnetic field in the entire space.

The general mathematical criteria of the topological instability were formulated by Gorbachev et al. (1988) as

$$\begin{cases} \mathbf{B}(\mathbf{r})|_{\mathbf{r}=\mathbf{r}^*} = 0, \\ \det \left\| \partial^2 \Phi / \partial r_i \partial r_j \right\|_{\mathbf{r}=\mathbf{r}^*} = 0. \end{cases} \quad (\text{A.2})$$

In other words, it is necessary to find the arrangement of magnetic sources admitting the null points \mathbf{r}^* in which the Euler–Poincaré topological indices change their signs.

In general, searching for the configurations satisfying equation (A.2) is a very hard mathematical task. By now, the corresponding analysis was performed only in the approximation of point-like sources (the effective ‘magnetic charges’), when the magnetic field can be presented as

$$\Phi(\mathbf{r}) = \sum_{i=1}^4 e_i \frac{\mathbf{r}}{r^3}; \quad (\text{A.3})$$

for the additional details, see papers by Gorbachev et al. (1988) and Somov (2008).

One of the simplest topologically-unstable arrangements, which was studied analytically in most detail in the previous works, is the T-type configuration formed by two pairs of sources of the opposite polarity located in the same plane. Just this arrangement was used in our numerical simulations. To avoid misunderstanding, let us emphasize that—from the viewpoint of rigorous mathematical terminology—the most of available criteria for the unstable topological configurations are the sufficient rather than necessary ones.