On existence of two different mechanisms for forming coronal mass ejections

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Abstract

We confirm the principal difference of the initiation phase between the impulsive and gradual CME motion trajectory revealed earlier in preliminary studies. Based on studying the dynamics of two impulsive CME (25 March 2008 and 13 June 2010), and also the MHD-approximation computations, we have come to a conclusion that forming impulsive CME starts under the solar photosphere and may be associated with supersonic emergence of magnetic tubes from the convective region. A radial velocity of such tubes at the photosphere level can reach hundreds of km s\textsuperscript{-1}, and their angular size $\approx (1-3)^{\circ}$. A probable reason of their rise from the convective region is the “slow wave” instability (the Parker instability).

Keywords: Coronal Mass Ejections, Initiation and Propagation; Waves, Shock

1. Introduction

A mechanism for forming coronal mass ejections (CME) has been the main problem in their studying over several decades. For years, a solar flare has been considered as a CME’s possible source. Theoretical papers consider the reconnection of magnetic field opposite polarity lines as the only mechanism for a flare (Giovanelli, 1946; Priest, 1982; Priest and Forbes, 2000; Somov, 2007). MHD theory predicts that the energy released during this process is shared roughly equally between plasma heating and kinetic energy of plasma ejection – “flare CME” or “flare jet” (Priest and Forbes, 2000). Direct observations confirm the presence of the reconnection mechanism during flares (Lin \textit{et al.}, 2005).

But the released energy distribution between various plasma components differs significantly from the MHD prediction. Thus, in Sui \textit{et al.} (2005) it was experimentally shown that in a mean-power isolated flare, with an X-ray class $\geq M1$, the flare’s total energy of $E_h \sim (2 - 3)10^{30}$ erg was distributed approximately as follows:

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• energy of accelerated particles (electrons) $E_p/E_h \approx (70 - 75)\%$;
• thermal energy of plasma $E_T/E_h \approx (20 - 25)\%$;
• kinetic energy of the plasma flow from the Sun ("flare CME (jet)"
  $E_{cme}/E_h \sim 1\%$.

Taking into account the error associated with an inaccuracy in volume the
heated plasma and the accelerated electrons energy spectrum lower boundary
(Sui et al., 2005), one may state the following:
• energy of accelerated particles exceeds the plasma thermal energy $E_T$ by a
  factor of 2-3;
• energy of a "flare CME (jet)" makes few percent of the total released energy $E_h$.

The fact that during flares the energy bulk turns into acceleration of charged
particles (electrons) tells about an essential role of the collective processes as-
sociated with the turbulent oscillation excitation. For most powerful flares with
an X-ray class $\geq X1$, accelerated particles include, except electrons, protons,
ions of other elements and nuclei, and their total energy exceeds $E_T$ by almost a
factor of 4-5 (Emslie et al., 2004). Also, the share of a "flare CME (jet)’’ energy
may be under 0.01$E_h$.

Thus, in all flares, regardless of their power, the reconnected magnetic field
energy majority falls on the collective particle acceleration, and the minority
falls on plasma heat, and still a greater minority falls on kinetic energy of a
"flare CME (jet)". At the same time, the kinetic energy of the most observed
powerful CMEs that are flare-associated in their origin by time and locality,
often twice and more exceeds the total energy of accelerated particles and re-
leased plasma heat (Emslie et al., 2004). Hence, it follows that the powerful
accompanying CMEs observed simultaneously with flares are not "flare CME
(jet)” and have another origin (Hundhausen, 1994). They exceed “flare CMEs
(jets)” both in their size, and in their characteristic velocities. Therefore, one
can observe “flare CME (jet)” only when there is no accompanying CME, i.e.
in the events with relatively small released energy. The reason for a “flare CME
(jet)” origin is the magnetic flux slowly emerging from under the photosphere
and its reconnection at its exit from the photosphere with the surrounding
magnetic field of opposite polarity. Such a pattern has been studied well theoret-
ically (Shimojo et al., 1996; Antiochos, 1998; Filippov, 1999; Asai et al., 2008;
Masson et al., 2009) and confirmed experimentally (Liu et al., 2011).

Powerful CMEs (“non-flare”) are classified into two groups by their motion
characteristics: “gradual” (slowly evolving) and “impulsive” (Sheele et al., 1999).
Impulsive are the fastest CMEs that are accelerated near the solar surface at
altitudes under $0.2 R_\odot$ relative to the limb (MacQueen and Fisher, 1983). How-
ever, fast CMEs may also origin as a result of a less fast acceleration occurring
within up to several solar radii (Plunkett et al., 2000; Yurchyshyn, 2002).

In Eselevich and Eselevich (2011) it was shown that the parameters reflecting
the difference between the impulsive and gradual CMEs in the physical nature
of their origin are the CME’s location, velocity and angular size at their origin.
The gradual CME origin location is in the corona at $0.1 R_\odot < h \leq 0.7 R_\odot$ above
the solar limb. They start their motion having an angular size within \( \approx (15-65)^\circ \) with an initial velocity \( V_0 \approx 0 \). Also, the flares that often accompany gradual CMEs (Hundhausen, 1994; Zhang et al., 2001) are not the main power source for them, and reflect the action of the trigger mechanism accompanying the CME motion start.

These peculiarities of the gradual CME origin and propagation qualitatively and, in some characteristics, quantitatively agree with the theory (Chen, 1996; Krall, Chen, and Santoro, 2000) that considers an eruption or sudden sun-outward motion of the magnetic flux rope localized in the solar corona the source of gradual CMEs. In a stationary state prior to eruption, the rope represents a plasma-filled magnetic field screw line arc pattern whose two footpoints are implanted in the solar photosphere. Along the rope, a prominence substance may be placed. An eruption probable reason, as per Krall, Chen, and Santoro (2000), may be, for example, a fast increase in the magnetic flux poloidal component in the rope. Possible are also some other reasons (Kuznetsov and Hood, 2000).

Also considered is a reconnection mechanism in the vertical current layer that is formed below the magnetic rope (Vršnak et al., 2004). In fact, various mechanisms may be in effect simultaneously. As per Forbes (2000), the onset of this or that mechanism leading to the eruption of the resting rope in the corona may be caused either by photospheric motions at the magnetic rope feet, or by a new magnetic flux emerging from under the photosphere.

Models for slowly emerging (at subsonic velocity) magnetic rope from a small depth from under the photosphere (\( \approx -2000 \) km) and its successive eruption in the corona like a CME due to various mechanisms have been considered in a number of papers (e.g., Archontis et al., 2004; Fan, 2005; Gibson and Fan, 2006; Archontis and Hood, 2010). In these models, the rope velocity is close to zero or very small prior to eruption, i.e., they also describe gradual CMEs.

As per experimental studies (Zhang et al., 2001), the gradual CME trajectory is characterized by three phases: the “initial phase” at which the rope velocity slowly grows from zero; the “impulsive phase” of fast acceleration and the “propagation phase” with approximately constant velocity.

Despite the relevance of the slowly emerging magnetic rope models, they possess a serious deficiency: this is an arbitrary selection of initial boundary conditions. Thereupon, of particular interest are studies of the convective region magnetic tube dynamics associated with the Parker instability (Romanov, Romanov, and Romanov, 1993a; Fan, Fisher, and McClymont, 1994). The problem of the magnetic tube rise from the convective region arbitrary depth is solved self-consistently in them. The computations made in Romanov, Romanov, and Romanov (1993a, 1993b) and having a preliminary character showed a principal possibility of magnetic tube rise into the solar atmosphere at high supersonic velocities. They revealed a dependence of the rise resultant velocity on: a) a magnetic tube emerge initial depth, b) an initial disturbance cross size, c) an initial tube magnetic strength at a emerge onset depth and d) an MHD-instability type whose evolution results in a tube ejection into the solar atmosphere.

In fact, these computations turned out the first basis of the mechanism for impulsive CME origin as a result of magnetic tubes (ropes) emerge at high supersonic velocities from the convective region into the solar atmosphere. They
predicted that the principal difference between impulsive and gradual CME trajectories should be expected at the initial phase in the solar atmosphere. A preliminary analysis of experimental data in Eselevich and Eselevich (2011) has confirmed this conclusion. It showed that the impulsive CME initial phase is characterized by the following features:

1. it starts from the photosphere;
2. the velocity at this phase varies insignificantly with distance and in time, and may be a few tens through hundreds of km s\(^{-1}\) for various CMEs;
3. the CME angular size at the photosphere level is estimated as \(d \leq (1-3)\degree\).

In this paper, investigated are the properties of two impulsive CMEs (one of which being analyzed from the SDO data). We give a theoretical basis and computation of a possibility to form impulsive CME as a result of magnetic tubes’ ejection from the convective region into the solar atmosphere at a supersonic velocity.

2. Method and data of analysis

When analyzing, we used the following data:

- EUV (211Å) images from AIA/SDO instrument, temporal resolution being \(\approx 12\) sec [http://www.lmsal.com/get_aia_data);
- EUV (171Å) images of the full solar disc and corona up to \(\approx 1.7R_\odot\) from EUVI (STEREO/Ahead) with the \(\approx 75\) s time resolution [Howard et al., 2008];
- corona images in the H\(\alpha\) line of neutral hydrogen obtained by the Digital Prominence Monitor (DPM) at the Mauna Loa Solar Observatory (MLSO), temporal resolution being \(\sim 3\) min [http://mlso.hao.ucar.edu/cgi-bin/mlso_data.cgi].

The AIA/SDO brightness data were represented like a difference brightness \(\Delta P = P(t) - P(t_0)\), where \(P(t_0)\) is the undisturbed brightness at \(t_0\) prior to the start of the event under consideration, \(P(t)\) is the disturbed brightness at any moment \(t > t_0\). The EUVI/STEREO data were represented like a running-difference brightness, for which \(t\) and \(t_0\) are the moments of the images adjacent in time. We studied the CME dynamics using the difference brightness \(\Delta P\) and distributions on the radius \(\Delta P(R)\) relative to the Sun center along the given position angle \(PA\) that was counted off in the images from the North Pole counterclockwise (Eselevich and Eselevich, 2008). The H\(\alpha\) images were represented like brightness isolines (Eselevich and Eselevich, 2011).

3. Analyzing impulsive CMEs

Let us consider two impulsive limb CMEs (longitude of their origin on the Sun being \(\Phi > 60\degree\)): 25 March 2008 and 13 June 2010. Each of these CMEs had been already studied earlier [Gopalswamy et al., 2009; Patsourakos, Vourlidas, and Kliem, 2010; Patsourakos, Vourlidas, and Stenborg, 2010; Temmer et al., 2010]. Therefore, basing on these papers, we will make a special accent on the initial phase of these events’ evolution.
3.1. 25 March 2008 event

For this CME, Figure 1A–E shows the running-difference images in EUV (from 171˚A EUVI/STEREO, Ahead) for six instants corresponding to this event. At 18:32:15 and 18:34:45 that are not shown, there is no CME. One manages to reliably record the CME first occurrence in Figure 1B at 18:38:30: it looks like a circular cavity with a reduced brightness near the solar surface. The CME angular size at this moment is \( \approx 3^\circ \) (two radial straight lines along the CME edges). The position of the cavity’s front boundary (point “A” in the \( PA = 95^\circ \) direction, median dashed line), coincides approximately with the vertex (point “B”) of the bright loop-like structure. The black plus sign shows them in Figure 1B (coinciding points “A” and “B”). At the next moment (Figure 1C) the cavity’s front edge “A” moves faster (\( V \approx 300 \text{ km s}^{-1} \)), than the loop vertex “B” (\( V \approx 90 \text{ km s}^{-1} \)) and, therefore, further we see them separately. As we move away from the Sun, a circular frontal structure (FS), confining the cavity, looks more and more visible around it. The structure’s angular size reaches \( d \approx 23^\circ \) when the cavity’s leading point “A”, approximately coinciding with the frontal structure maximum position, is recorded at \( R_A \approx 1.39R_\odot \). The loop moving more slowly ceases to be visible inside the cavity by 18:47:15 (Figure 1E).

According to [Patsourakos, Vourlidas, and Kliem, 2010] and [Eselevich and Eselevich, 2011], the CME circular frontal structure, when observed in 171˚A and in white light at close instants, approximately coincide in shape and location, differing only in the frontal structure ring thickness. It allows to identify as CME frontal structure the bright ring covering a cavity in Figure 1E.

The leading point “A” motion velocity dependencies on distance \( V(R) \) and time \( V(t) \) are exhibited in Figure 2A and 2B, respectively (black circles). One may single out a few peculiarities characteristic of these dependences.

1. At the path segment starting with \( R \approx 1.04R_\odot \) and up to \( R \approx 1.33R_\odot \), the CME cavity leading point “A” velocity is almost constant (Figure 2A). (The first-in-time point in Figure 2A was estimated as per the cavity position at its first occurrence in the assumption that, at the preceding instant of measurement, the cavity was at the solar photosphere). In the \( V(t) \) dependence, this segment \( t \approx 18:37:00 - 18:46:30 \) corresponds to the “initial phase”. At distances \( R \geq 1.33R_\odot \), the velocity grows fast (Figure 2A) which, in the \( V(t) \) dependence corresponds to the onset of the acceleration “impulsive phase”, approximately, at 18:46:30 (Figure 2B).

2. The \( V(R) \) linear extrapolation up to the photosphere level (the horizontal dashed line in Figure 2A) provides velocity values of \( V_0 \approx 300 \text{ km s}^{-1} \) close to it.

The assumed angular size of the CME at the photosphere level is \( d_0 \leq 3^\circ \). These CME cavity dynamics peculiarities allow one to interpret it as a manifestation of the magnetic tube (rope) whose size is under \( d_0 \) thrown out into the solar atmosphere. This conclusion agrees with the inferences by [Patsourakos, Vourlidas, and Kliem, 2010] that the moving and expanding cavity (it is termed a bubble there) appear at an instant \( t \geq 18:35 \), but is absent before that, and this is a manifestation of a CME flux rope, having a smaller size. It allows one to assume that impulsive
CMEs may be thrown out like magnetic ropes from the convective region at a great velocity essentially exceeding the speed of sound (speed of sound $V_s \approx 6-8$ km s$^{-1}$ at the photosphere level).

It is interesting to note that the $V(t)$ curve profile, starting with 18:43:00 and further, agrees well with the $V(t)$ curve built up from the EUVI (Behind) data in Temmer et al. (2010) (light circles in Figure 2B). The difference between black
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Figure 2. Velocity dependences on distance (A) and time (B) of the CME cavity’s leading point “A” (black circles) and leading point “F” of the $H_\alpha$ profile $P_{\alpha}(R)$ along $PA = 100^\circ$ (black squares); (C-G) Radial $H_\alpha$ profiles $P_{\alpha}(R)$ along $PA = 100^\circ$ for consecutive instants on 25 March 2008.

and light circles starts at times under $t_1 \approx 18:43:00$. Obviously, the reason for this is the fact that, in the “Behind” case at $t < t_1$, the point “A” motion occurs on the solar disc and observing the cavity is impeded through the presence of bright loop structures whose drift velocity is actually recorded. In fact, it is the velocity of the loop vertex “B” (black triangles in Figure 2B) thrice as less as the cavity’s front boundary velocity (black circles) that has a velocity close to the values designated in light circles for $t < 18:42:00$.

An important additional argument in support of the $V(R)$ linear approximation up to the solar photosphere for the CME cavity’s front boundary in Figures 2A and 2B is analyzing the kinematics of a powerful ejection observed in $H_\alpha$ accompanying this CME. Let us consider this process in greater detail. First of all, a few notes on the starting conditions of this process and terms.

1. In literature, such a phenomenon is routinely termed an active prominence or “surge” when observed in the $H_\alpha$ line and “jet” when observed in EUV and soft X-ray (Priest, 1982). To simplify, we will be terming all the motions in $H_\alpha$ jets.

2. The jet’s escape occurred from the NOAA active region 10989 located near the limb (its spot group position is $\approx S10 E85$).

3. The temperature of quiet, eruptive and active prominence observed in $H_\alpha$ does not exceed $10^4 K$ (Moore et al., 2010).

4. When observing an active region in the $H_\alpha$ line, even in the absence of CME-like strong sporadic phenomena or flares, one records motions of a comparatively cold ($< 10^4 K$) substance at altitudes significantly smaller than altitudes of quiet prominences ($< 15000$ km) (Priest, 1982) along the magnetic field lines.
Thus, obviously thereupon that the considered impulsive CME arose in the active region located near the limb, its occurrence was preceded by a few very faint ejections of cold plasma at 50-100 km s\(^{-1}\) within about 30 minutes. In Figure 1G–I (the \(P_H\) brightness isolines in \(H_\alpha\)) they are seen like weak jets rising and then returning onto the Sun at 18:25:04 and 18:27:58. In Figure 2C,D, we give the examples of several radial profiles of the brightness in \(H_\alpha\) towards \(PA = 100^\circ\) for weak jets within 18:06:58-18:42:58. Their rise maximal height for 18:16:03 (pluses) and 18:42:58 (light circles) did not exceed \(h \approx 0.025R_\odot\) above the solar surface. There was no quasistationary prominence on the limb prior to the CME emergence. It is seen, for example, in Figure 1G at 18:18:59 and later, i.e., approximately, starting 19 minutes before the CME first emergence in the cavity’s corona.

The motion of the CME proper is accompanied by a powerful ejection of solar material as seen in Figure 1J–L. Let us term it Jet. Since the temperature of a weak jet and powerful Jet is circa equal (∼10^4 K) one may estimate the relative mass of the substance ejected, assuming \(M \sim \int P_H dS\), where \(S\) is the full area of the observed jet. It turned out that for the powerful Jet this value \(M_\text{J}\) exceeds by almost a factor of 2-3 \(M_j\) for weak jets.

The powerful Jet moves, practically, radially until 18:46:10 (Figure 1J), and then swerves, and after 18:49:19 (Figure 1K,L) returns onto the solar surface. Figure 2E–G shows radial profiles of the brightness in \(H_\alpha\) in consecutive instants passing through the Jet (\(PA = 100^\circ\)). These profiles allow one to trace the Jet dynamics and compare it to the CME dynamics. A cavity corresponding to the CME is recorded in the solar atmosphere, for the first time, at 18:38:30 (Figure 1B). There are no Jet signs in the \(H_\alpha\) brightness profile corresponding to the later instant, 18:42:58 (light circles in Figure 2D). This means that it is the CME that initiates the Jet, but not vice versa. An unexpectedly huge mass of cold plasma compared with that of the weak jet also testifies in favor of such a forced mechanism for the Jet emergence. In the \(H_\alpha\) brightness profiles (Figure 2E–G) one can single out the fastest part for the Jet (F-arrow). A fast reduction of the signal maximum \(M\) with time and then its vanishing in Figure 2E–G reflects the process of the Jet deviation from the radial direction. (We note that in Figure 2E the signal is saturated, i.e. the true value of the maximum \(M\) may be essentially greater than the shown value \(P_H \approx 900\)). The Jet fastest part velocity is shown by a dashed line with black small squares in Figure 2A,B. Its initial value near the photosphere is close to the CME cavity’s leading part velocity (black circles in Figure 2A,B). It confirms the assumption that the reason for the Jet, most likely, is the CME cavity’s escape from the Sun at a great speed, at least, no lower than the Jet velocity (∼330 km s\(^{-1}\)).

Let us note that the presence of Jet is not a mandatory signature during an impulsive CME.

3.2. 13 June 2010 event

Figure 3A–J shows the difference brightness images (relative to \(t_0 = 05:32:02\)) for this CME in EUV (211A AIA/SDO data) for 9 instants corresponding to this event. The first appearance of the cavity was observed at 05:32:50 inside a
small loop-like structure (numeral 1 in Figure 3B). Its angular size is $d \approx 1.7^\circ$. This means that the cavity size is slightly smaller. Such an onset is analogous to the onset of the CME above (25 March 2008). But the further evolution of this event allows one to reveal a number of interesting peculiarities due to the AIA high temporal resolution, which enables us to advance in understanding this phenomenon. Thus, starting with 05:33:50 (Figure 3 does not show this instant), the formation of four more similar loop-like Structures starts to become visible ahead of loop-like Structure 1, at different fixed distances, 2, 3, 4, and 5, respectively, in Figure 3C. In the successive image in Figure 3D, they are seen more clearly and remain fixed to the instants defined for every structure.

The cavity’s center in Figure 3B is located at $R_1 \approx 1.022R_\odot$ at the first appearance. It is obvious that the appearance of Structures 2, 3, 4, 5 is associated with the disturbances that are caused by the cavity appearance in the corona at $R_1$. Under the impact of the disturbance, the structures in the difference
brightness, invisible previously, shift and become visible. The first appearance of the farthest structure 5 is recorded at $t \approx 05:33:50$ at $R_5 \approx 1.174 R_\odot$ (Figure 3 does not show this instant). Time dependence of the above-limb height of the five loop-like structures’ vertexes is presented in Figure 4. The dashed straight line inclination (left in Figure 4) is determined by the appearance delay time of every of these structures at different altitudes $h$. Its crossing with the photosphere provides instant $t_0 \approx 05:32:30$ of the operation onset for the source of these disturbances (arrow in Figure 4). At segment $h \approx (0-0.2)R_\odot$, the mean disturbance propagation velocity $V_{dist} \approx 1600 \pm 800$ km s$^{-1}$, and it is comparable with the mean Alfvén velocity at these distances (Gopalswamy et al., 2009).

The presence of Structures 1-5 formed on the expanding cavity’s motion path is, to a certain extent, an indicator of the cavity dynamics at these distances. First of all, one may see that the cavity, moving radially, expands evenly every which way so that, at all these stages, it is approximately described by a circle. The visible motion of every structure starts when the cavity reaches the latter and carries it away. First, the cavity reaches structure 1 that starts moving at $\approx 05:33:20$ (in Figure 4), then is expands and disappears. Structure 2 starts moving at $\approx 05:35:38$, then, expanding, disappears. Structure 3 starts moving at $\approx 05:36:02$, then, expanding, disappears. Structure 4 starts moving at $\approx 05:36:38$, expanding, it merges with Structure 5 forming the ultimate shape of the CME frontal structure. The velocities of these structures reflecting the cavity’s propagation velocity make $V \approx 280-290$ km s$^{-1}$ (dashed straight lines in the right part of Figure 4). It is obvious that the cavity’s traveling velocity is not less than this velocity. The instants of the motion onset (or the cavity’s carrying them away) are most clearly visible for Structures 3-5. Assuming that the cavity’s source and the cavity proper emerge on the solar surface at $t_0$, we
obtain an estimate of the cavity’s mean velocity \( V_{\text{cav}} \approx 370-480 \text{ km s}^{-1} \) over the interval \( \approx 05:32:30-05:37:00 \) (an inclination of two bold straight lines in Figure 4). By analogy with the 25 March 2008, it is only natural to assume that a magnetic tube of a smaller size than the cavity ejected from the convective region in the solar atmosphere at \( V_{\text{cav}} \approx 370-480 \text{ km s}^{-1} \) is the cavity’s source. The obtained value \( V_{\text{cav}} \) is close to the CME velocity over the interval 05:37:00-05:38:00 measured in [Patsourakos, Vourlidas, and Stenborg (2010)](Figure 4) that made \( V \approx 350-400 \text{ km s}^{-1} \).

To summarize this Section, we will note the following. Recent direct measurements of the polarized signal Doppler shift near the FeI 5250.2 \( \lambda \) line at the IMaX instrument within the Sunrise stratospheric balloon-born telescope provided a supersonic value of magnetic tube rising velocity at the photosphere level \( \approx 12 \text{ km s}^{-1} \) [Borrero et al., 2010]. Moreover, it was made at the temporal resolution limit of the instrument. Thus, a possibility of ejecting magnetic tubes at supersonic velocities into the solar atmosphere has not only indirect, but also direct experimental evidence. But, in order to record magnetic tube rising at high velocities, it is necessary to increase the temporal resolution of present-day instruments.

4. Discussing the mechanism for origin of impulsive CMEs

From the stated above it follows that impulsive CMEs may gain initial velocity in the convective region where the medium plasma is ideal and optically thick. In this region, strong frozen magnetic field represents an ensemble of magnetic flux ropes (magnetic tubes) [Stenflo, 1973], and the plasma motion is well described in the ideal MHD approximation. It imposes some characteristic restrictions on the problem: the plasma motion is self-consistent and this does not allow one to simply bring in additional power sources or field twists like, for example, it is the case when considering magnetic ropes in the corona [Chen, 1996]. All the sources require a complete substantiation of their nature. Under these circumstances, the problem to search for a mechanism for forming impulsive CMEs is put as an as a problem with initial conditions, after which the tube evolution is described self-consistently by a set of MHD equations. To describe the dynamics of a separate magnetic tube, we use an assumption that the tube parameters across the cut are circa homogenous. This assumption is well-substantiated (droppable values have the infinitesimal order of \( \sim 10^{-2}-10^{-6} \)).

When transiting from of the MHD three-dimensional system to the thin magnetic tube approximation [Romanov, Romanov, and Romanov, 1993a], one takes into account the cross balance of internal \((i)\) and external \((e)\) pressures

\[
p_i + \frac{H^2}{8\pi} \approx p_e, \tag{1}
\]

after which an MHD motion equation

\[
\rho \left[ \frac{\partial \vec{v}}{\partial t} + (\vec{v}, \nabla) \vec{v} \right] = -\nabla \left[ p + \frac{H^2}{8\pi} \right] + \frac{1}{4\pi} (\vec{H}, \nabla) \vec{H} + \rho \vec{g} \tag{2}
\]
assumes the form

\[ \rho_i \frac{d\vec{v}}{dt} = -\nabla p_e + \rho_i \vec{g} + \frac{1}{4\pi} (\vec{H}, \nabla) \vec{H}. \] (3)

The main forces are the pressure gradient, gravity and tensile force of the magnetic field. In a hydrostatic medium \((\nabla p_e = \rho_e \vec{g})\) the first two unite into the buoyancy force \((\rho_i - \rho_e) \vec{g}\).

Papers [Romanov, Romanov, and Romanov, 1993a; Fan, Fisher, and McClymont, 1994] considered the dynamics of a similar magnetic tube rising in detail. Below, we present the principal results most relevant in terms of studying the initial stage of impulsive CME formation.

1. At lateral compression, a part of the external pressure is counterbalanced by the magnetic field \(p_{mag} = H^2/(8\pi) \propto \rho^2\), which changes the effective adiabatic index of the magnetized plasma and results in that the convective instability increment is nonzero.

2. The “slow wave” instability wave (the Parker instability) is the key instability. Its mechanism is as follows: at a form slight disturbance, the tube plasma flows downward from the rising part. If the disturbance wave length is great enough, the field tensile force is not capable of compensating the buoyancy force upward on the radius, and the total pressure gradient does not hinder with the plasma flow along the tube. As a result, the loop vertex continues rising with an increasing velocity.

3. The input parameters of the problem are only the tube’s initial state near the convective region bottom and distribution of the outer medium parameters; the system of equations has been obtained directly from MHD and is self-consistent.

The latter condition is a strong point of the model since without bringing in model sources and by only selecting the initial state we reproduce simultaneously a wide spectrum of the observed peculiarities: range of latitudes for sunspot emergence; sunspot inclination angle towards the equator and its dependence on the field strength and position; asymmetry between the western and eastern sunspots, etc. All this justifies the quality of the model.

Figure 5 presents the result of modeling a rising of a magnetic tube from the rest state [Romanov et al., 2010]. Initially, the tube rests horizontally in the equatorial plane. Affected by the Parker instability, an arc whose vertex rises upward is formed and punches the photosphere. Although above the photosphere the used equation of energy is already inapplicable (radiant heat exchange becomes volumetric), the accumulated impulse changes mainly under the influence of the field tensile force and the buoyancy force so that the results are a good order-of-magnitude estimate. The tube reaches the photosphere fast, with a peak velocity of the order of 100 km s\(^{-1}\) (Figure 5).

5. Conclusions

1. We have confirmed the key difference established earlier in [Eselevich and Eselevich, 2011] between the impulsive and gradual CME trajectory “initial phase”.
2. We have arrived at the conclusion that forming impulsive CMEs starts under the solar photosphere and may be associated with supersonic emergence of magnetic tubes (ropes) from the convective region. At the photosphere level, the radial velocity of such tubes may reach up to hundreds of km s\(^{-1}\), and their angular size may be \(d \approx (1-3)\). 

3. A probable reason for supersonic rise of magnetic tubes (ropes) from the convective region is the “slow wave” instability (the Parker instability).

Acknowledgements. We thank the teams controlling all the instruments whose data have been used in this study for their efforts and open data policies: the ESA and NASA STEREO/SECCHI and SDO/AIA telescopes. Courtesy of the Mauna Loa Solar Observatory, operated by the High Altitude Observatory, as part of the National Center for Atmospheric Research (NCAR). NCAR is supported by the National Science Foundation. The research was supported by the Russian Foundation of Basic Research Grants No. 09-02-00165a, No.10-02-00607a. We thank Yuri Kaplunenko for the help in translation into the English.

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