Velocity scaling and coupling of prominences and coronal mass ejections

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Abstract. We describe binary and ternary types of coupled coronal mass ejections and prominences based on the new classification of internal, proper body and external velocity field characteristics of the slow, medium and fast flows.

Index Terms. Coronal mass ejections, dimensionless scaling, prominences, velocity.

1. Introduction

Eruptive processes on the Sun look similar or widely different, from case to case, because of their complicated geometry. The bulk plasma velocity fields inside and outside coronal mass ejections (CMEs) and prominences can be considered as consisting of: 1) internal, 2) proper as a body, and 3) external or background components. Purely subjective and rather arbitrary quantitative categories of slow (S), medium (M) and fast (F) speeds are often used in the literature. If we apply the binary classification only with two categories (S, F), eight different classes of moving objects appear according to simple combinatorial rules. If we apply the ternary classification (S, M, F), twenty-seven different classes can be indicated.

We discuss shortly these discrete classes with possible subclasses. Their physical similarities and differences can be further quantified when using the physical dimensionless scaling approach, leading to continuous/discontinuous field descriptions based on MHD formulations with radiation and dissipation or kinetic equations. Deterministic descriptions being complicated, statistical methods and the corresponding nomenclature dominate. We also refine concepts of usual and extreme events.

2. Dimensionless scaling approach

It is not a good idea to consider coronal mass ejections and erupting prominences separately, but we will not avoid this tradition for a moment. In reality, they are strongly coupled. There are at least eight physically different and not reducible dimensionless parameters, which govern a coronal mass ejection or prominence, considered separately or as a whole body. These parameters are listed in Table 1. It is quite understandable that the number of possible combinations of scaling between parameters is very big. Nevertheless, typical situations have similar scaling, when extreme cases (small and large events) obey different laws in this sense. One can easily introduce absolute and conditional extremes as in the standard mathematical analysis using this method.

Table 1. Useful dimensionless parameters normalized via the bulk flow velocity.

Name	Description	Role
Strouhal	Time / Flight times	Time scales
Knudsen	Mean free path / Size	Length scales
Velocity-emission	Kinetic energy / EM emission	Plasma density
Mach	Bulk speed / Thermal speed	Temperature
Magnetic Mach	Bulk speed / Alfvén speed	Magnetic field
Froude	Velocity / Free escape speed	Gravity
Faraday	Potential / Inductive	Electric field
Trieste numbers	Inflows / Inner flows	Openness degrees

The selection of parameters and normalization could be arbitrary and not reference frame invariant. Here we adopted the normalization using the bulk velocity, which is comfortable for our purposes of the study of moving objects – eruptive prominences and coronal mass ejections. Please note, that values of Reynolds and magnetic Reynolds numbers, as well as some other well known dimensionless parameters can be easily expressed as combinations of these 'basic' parameters. The selected 'basis" is physically 'complete and orthogonal' in the usual multidimensional geometry sense and can be algebraically replaced according to the standard generalized coordinate system transformations in the space of physical parameters of the MHD formulation with dissipation and radiation (see details in Veselovsky, 1996; 1999; 2001).

Naturally, the fundamental equations for the description of the extremities remain the same. This categorization is needed only for our better representation and classification of 'perturbations on the Sun'. This quantitative approach could also be useful for putting the end to fruitless discussions in the current literature, for example discussions about mythological 'primary energy releases' or non-existing cause-to-sequence relations between flares and CMEs. We are dealing with coupled non-local and not point-like events in space, with finite times and not delta-functions.

If we consider CMEs or prominences as 'bodies', we can distinguish internal motions inside the bodies, external motions outside them and motions crossing the boundaries of the body. Hence, one obtains several characteristic situations in this simplest case: S or F flows inside, S or F outside, S or F crossing boundaries. The interaction of bodies with the surrounding medium (background) depends on the combination of these parameters. For example, it could be with shocks or without them depending on the Mach and Mach-Alfvén numbers. The body can be 'penetrable" or not depending on Trieste numbers, which characterize the physical openness degree of the system under consideration. Prominences are essentially 'penetrable' for mass, momentum and energy flows connecting them with large photospheric reservoirs of mass, momentum and energy for dynamical transformations. In many instances, they are just visible sites of the cold plasma temporary accumulation in summits of magnetic loops organized in arcades. Hence, attempts to consider prominences as isolated bodies are very crude.

Flows along and across magnetic fields were documented and with caution, but in general correctly interpreted in first classical and unprecedented photographic observations (Pettit, 1919). It is curious, that the right idea of the bulk outflow (or solar wind) was not admitted a priori and discarded. Stereo couples were first used for the determination of the velocity map in this work. Let us look more attentively at this very worthy and unique material.

3. Interpretation of Pettit's observations

The huge rising prominence was observed and photographed during more than 7 hours on May 29, 1919. By the way, it was the famous eclipse day and other observations are available of this prominence. The erupting prominence consisted of the loops with internal motions, which were well documented. The inhomogeneous velocity field was accurately measured during all phases of ascent from 200 Mm up to 760 Mm projected height above the limb. We refer mainly to Fig. 3 and Plates in the paper by E. Pettit (1919), but do not reproduce them here.

If we superimpose the overall radial expansion velocity field of the prominence with more local motions seen in these images, we come to several interesting conclusions: 1) whip-like behavior is the consequence of the superposition of the overall radial expansion and the siphon flow from one leg; 2) large scale magnetic reconnection is not essential for explanation – the overall loop-like topology is preserved for eight hours during the prominence eruption from its beginning until the end of observations, when the process was nearly completed; 3) many chaotic irregular motions are clearly seen. We can comment on the points 1) and 2) above. The velocity pattern in some sense resembles the plasma flow in the magnetosphere with topologically different regions – closed and open stream lines with the separatrix between them on the plasmapause. See Brice (1967) and many later papers on this subject for comparison. The phenomenon has nothing to do with the magnetic reconnection. We clearly see in this event that the large scale magnetic reconnection is not necessary for the plasma outflow from the Sun during the eruption (the same is observed in the magnetosphere).

Up- and down flows in the solar atmosphere persist in the turbosphere around the Sun. Only uplifts are occurred higher beyond the turbopause. Zero point in the instantaneous velocity field considered along selected stream line of the detaching plasma element escaping from the Sun exists at some distance from the solar surface. The network of such points forms the temporary sources of the mass for the solar wind outflow (Veselovsky, 1996). This network is distributed at some surface termed as turbopause around the Sun. Turbosphere is far from being a spherical steady state boundary. It is complicated and dynamical. Loops with both legs on the Sun and whips with only one leg on the Sun are rather common features in the dynamical solar atmosphere.

4. Binary classification

In the case of the binary classification, only two properties can be prescribed to the morphological elements. In our case they are represented by slow (S) or fast (F) velocities. Categories S and F can be quantitatively defined by fixed rules, optionally based on some criteria using one dimensionless parameter, which can be large in one case and small in the opposite situation. 'Large' and 'small' mean here >1 and <1. Practically, this categorization can mean supersonic and subsonic, superalfvénic and subalfvénic etc., but is often arbitrarily selected. Situations can be as follows (see Table l.2): 1) slow proper and outside velocity ('resting body') SS; 2) slow proper, but fast outside ('pushing') SF; 3) fast inside, but slow proper motion ('pulling') FS; 4) fast everywhere ('ejecta surrounded by the high speed stream') FF. All these four cases are common and can be recognized in observations of 'laminar' eruptions when we neglect internal motions.

Table 2. Binary classification of proper and external flow types.

Types/ motions	SS	SF	FS	FF
Proper motions	Slow	Slow	Fast	Fast
External motions	Slow	Fast	Slow	Fast

If we add the degree of freedom for internal motions, the number of variants is twice as large and will be eight taking into account 'turbulent' ejecta. Examples of this kind can be found in the broad LASCO/SOHO gallery of movies.

5. Ternary classification

Ternary classification contains three degrees (S, M, F) of the velocity characterization for the body and the background. Accordingly, there are 27 different combinations conceivable. We do not present all of them here in details, but only mark broad variety and rather big arbitrariness in available qualitative descriptions when reading numerous papers about eruptive prominences and CMEs. The strongest perturbations appear to be in the corner (F, F), when the weakest occupy (S, S) place in this generalized space with all intermediate situations in between them. Practically, the value of such characterizations is limited and can even be misleading, when it is performed without quantitative discriminations. The use of dimensionless parameters is more preferable and unambiguous.

6. Discussion

Several interesting results of our new classification schemes can be indicated. Whip-like and loop-like eruptive prominences belong to the topologically different families with and without reconnections in the velocity field. (Reconnection is understood here as the topological transition with the formation or annihilation of neutral points in the field under consideration.) Another important conclusion consists in the fact that the magnetic reconnection is not necessary and not a sufficient ingredient of all eruptive processes on the Sun and in the heliosphere. Prominences and CMEs are coupled in a complicated way, which is now better understood with the new and objective classification schemes instead of arbitrary ones. Nevertheless, we find that traditional nomenclature and old 'naive' descriptions were sufficiently precise and useful in the classic works. For example, phenomenological categorizations of quiet, activated and eruptive prominences are capturing the physical situations rather well. Opposite examples of confusions can be often found in more recent sophisticated literature.

7. Conclusions

1. Dimensionless velocity scaling gives unambiguous classification of ejection on the Sun.
2. 8 binary and 27 ternary types of the velocity field can be indicated.
3. Velocity field reconnection is observed during ejection as "loop - whip shape transformation."
4. Classical observations by E. Pettit are interpreted using this approach: siphon + solar wind = whip.

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