STRONG PERTURBATIONS ON THE SUN AND IN THE HELIOSPHERE: SCALING OF SIMILAR AND INDIVIDUAL CHARACTERISTICS

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Contents

- Dimensionless parameters in MHD with dissipation and radiation
- Eruptions with/without topological changes (‘reconnection’)
- Velocity scaling and velocity ‘reconnection’
- Classical case interpretation (eruption of May 15, 1919 on the Sun)
- Conclusions

Dimensionless scaling: Alfvén wave

- **Given:**

1) magnetic field B;
2) mass density ρ

- **Problem:**

Find characteristic velocity of perturbations

- **Answer:**

$\mathbf{V_A \sim B/\rho^{1/2}}$ **(H. Alfvén, 1942)**

Dimensionless scaling: strong explosions in the atmosphere
(Sedov's solution)

- **Given:**

1) Strong point-like explosion in the homogeneous atmosphere
2) **E -** energy released
3) **ρ** -density of the atmosphere
4) t – time after explosion

- **Problem:**

Find the shock velocity **u(t)** as a function of time

- **Solution:**

Dimensionless parameter was found (L.I. Sedov) $\xi = r\,(\rho/E\,t^2)^{1/5}$

- **Answer:**

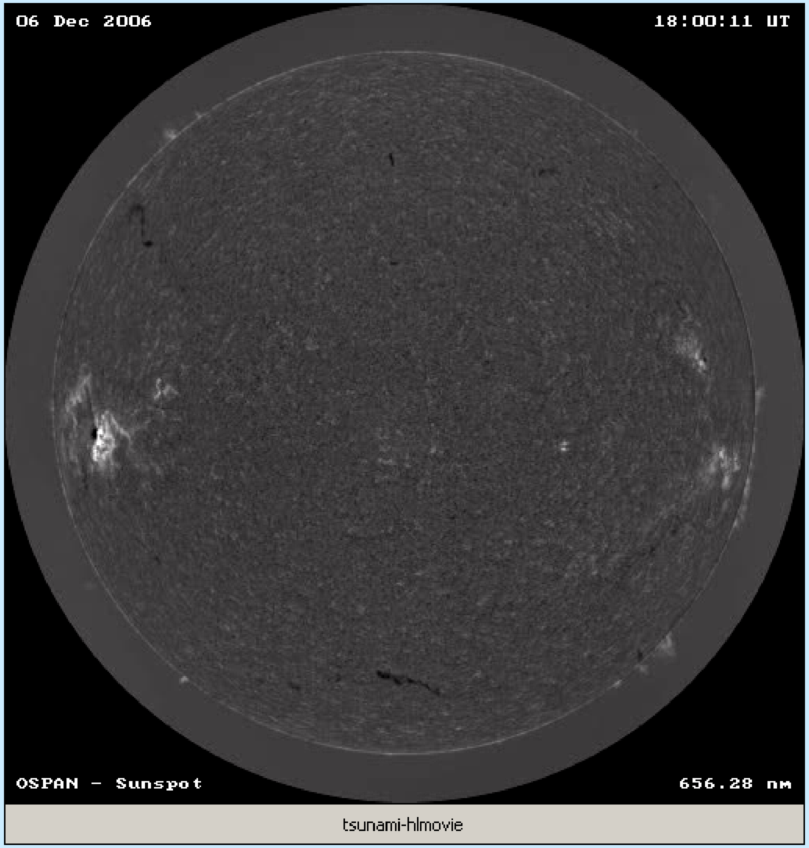
$$\mathbf{u(t) \sim (E/\rho t^3)^{1/5}}$$

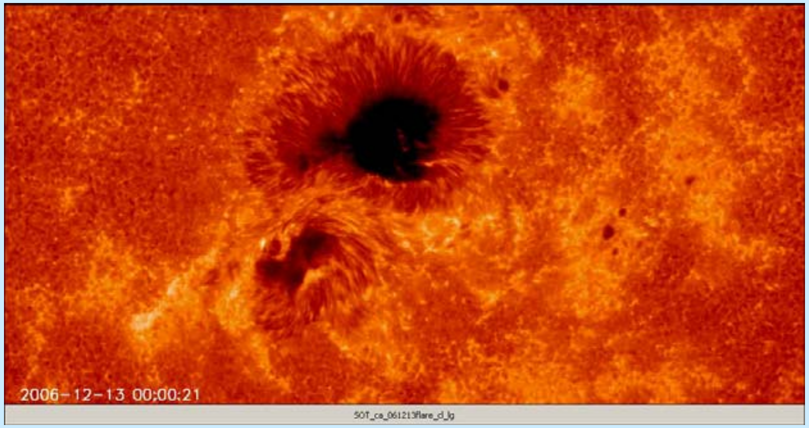
- **Practical implications: Energy of the explosion E can be estimated from kinematics of the strong shocks**

Explosive wave

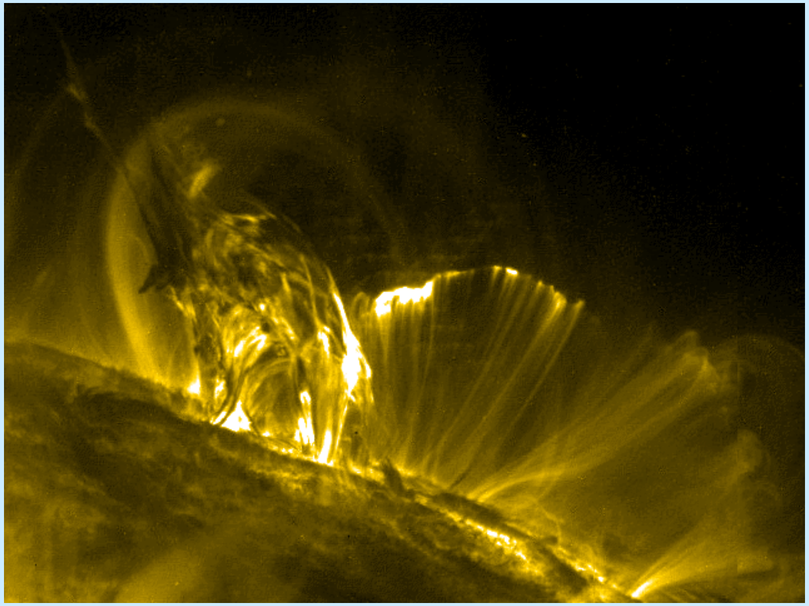
Hinode observations

December 6, 2006 (656.28 nm)





Complicated dynamical geometry of arcades:

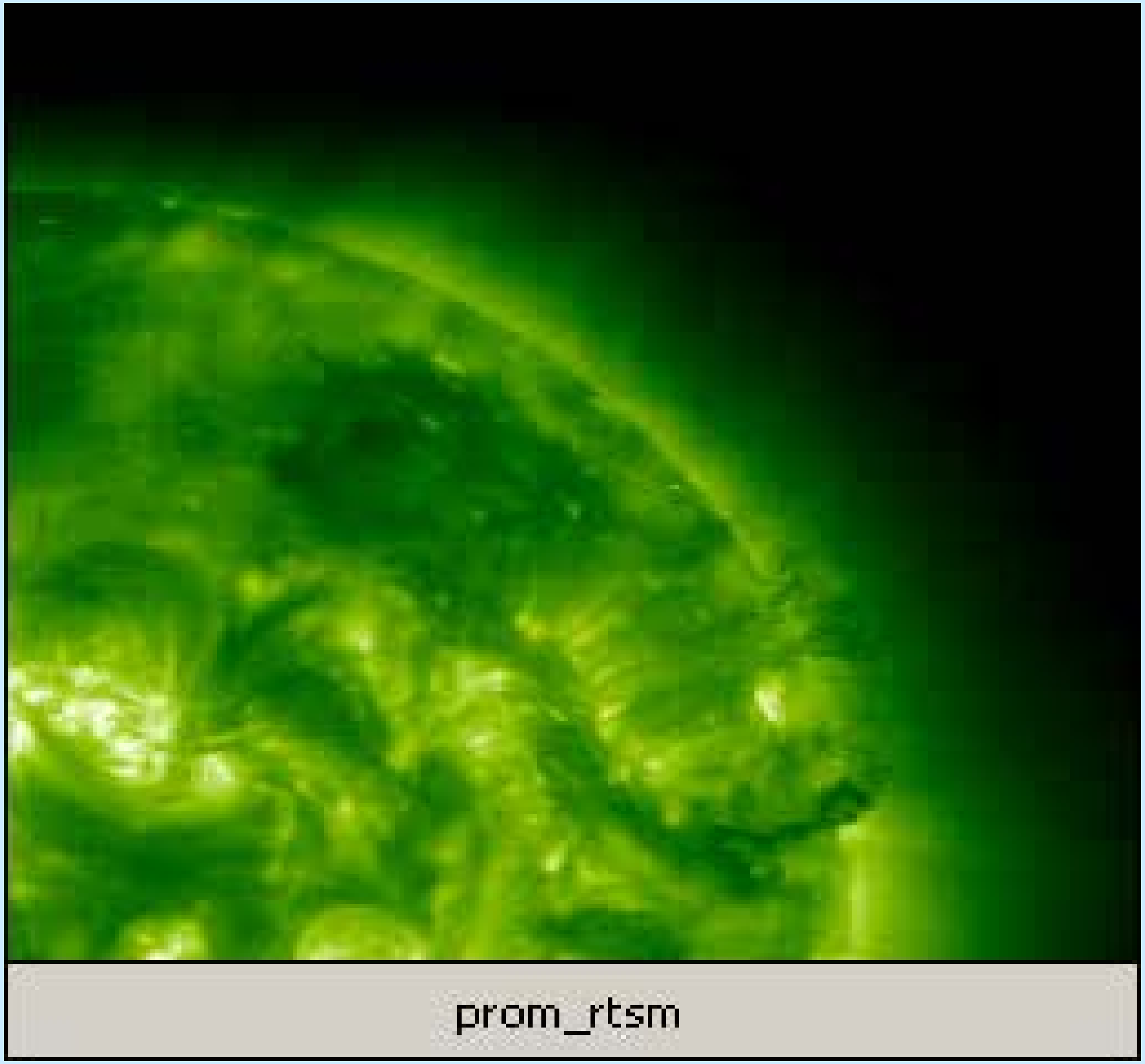


- Spurious "reconnections" and X-points: projections of twisted loops
- Spurious "crossings of the loops": the same as above
- Spurious "plasmoids":

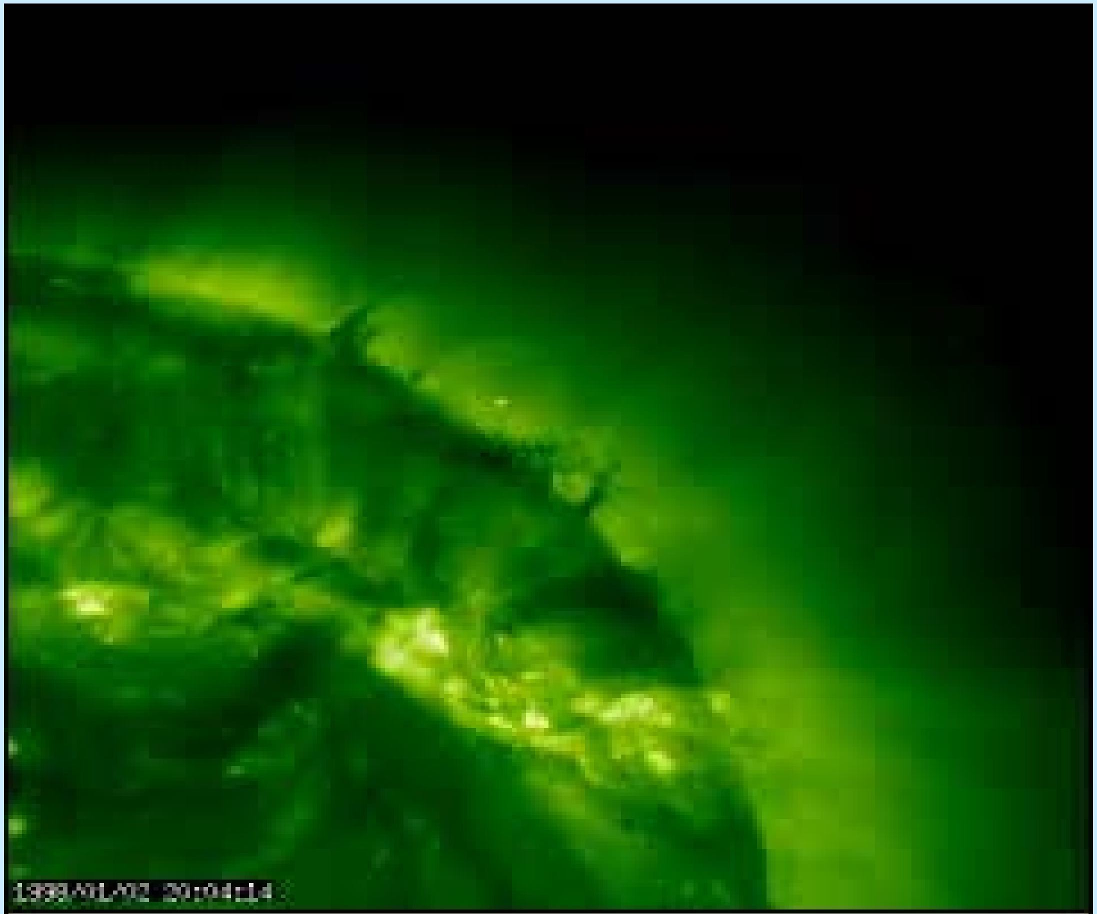
brighter summits of the loops

(an example from the TRACE "gold mine")

Projection effects



Multi-scale nature of erupting prominences



EIT195_eruptsm

Conservation Laws

mass

momentum

energy

Governing MHD equations with dissipation and radiation

$$\frac{\partial \rho}{\partial t} + \vec{\nabla}(\rho \vec{v}) = 0, \qquad (1)$$

$$\rho\left\{\frac{\partial \vec{v}}{\partial t} + (\vec{v}\vec{\nabla})\vec{v}\right\} + \vec{\nabla} p - \frac{1}{4\pi}[[\vec{\nabla} \times \vec{B}] \times \vec{B}] + \qquad (2)$$

$$+ \vec{F}_{viscous} + \vec{F}_{gravity} = 0$$

$$\frac{\partial}{\partial t}(\rho u + \frac{1}{2}\rho v^2) + \frac{\partial}{\partial x_i}(\rho v_i w + \rho v_i \frac{v^2}{2} + \rho v_k \sigma'_{ik} - \kappa \frac{\partial T}{\partial x_i} + \qquad (3)$$

$$+ \frac{1}{4\pi} e_{ikl} e_{lmn} v_m B_k B_n + \frac{c}{4\pi\sigma} e_{ikl}\, j_k B_l) = -L + A$$

Symbolic shape of equations

$$\frac{\partial \rho}{\partial t} + \vec{\nabla}(\rho \vec{v}) = 0 , \qquad (4)$$

$$S^{-1} \quad + \quad 1$$

$$\rho \left\{ \frac{\partial \vec{v}}{\partial t} + (\vec{v}\vec{\nabla})\vec{v} \right\} = -\vec{\nabla} p + \frac{1}{4\pi}[[\vec{\nabla} \times \vec{B}] \times \vec{B}] + \qquad (5)$$
$$+ \vec{F}_{viscous} + \vec{F}_{gravity}$$

$$S^{-1} \quad + \quad 1 \quad = \quad M^{-2} \quad + \quad M_A^{-2} \quad + \quad \mathrm{Re}^{-1} \quad + \quad Fr^{-!}$$

$$\frac{\partial}{\partial t}(\rho u + \frac{1}{2}\rho v^2) + \frac{\partial}{\partial x_i}(\rho v_i w + \rho v_i \frac{v^2}{2} + \rho v_k \sigma'_{ik} - \kappa \frac{\partial T}{\partial x_i} + \qquad (6)$$
$$+ \frac{1}{4\pi} e_{ikl} e_{lmn} v_m B_k B_n + \frac{c}{4\pi\sigma} e_{ikl} j_k B_l) = -L + A$$

$$M^{-2} S^{-1} \quad + \quad S^{-1} \quad + \quad M^{-2} \quad + \quad 1 \quad + \quad \mathrm{Re}^{-1} \quad + \quad \mathrm{Re}^{-1} M^{-2} \mathrm{Pr}^{-1}$$
$$+ \quad M_A^{-!} \quad + \quad M_A^{-2} \mathrm{Re}_m^{-1} \quad = \quad V_e \quad + \quad Fr^{-1}$$

Dimensionless parameters

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

Table 3. Irreducible and full set of independent orthogonal dimensionless parameters in the ‘velocity normalised basis’

Symbol	Name	Formula / Definition	Signifiance
M	Mach number	v/c_s	Temperature
Ma	Magnetic Mach (Mach – Alfvén)	v/V_A	Magnetic field and currents
S	Strouhal	vt/x	Time
Tr	Trieste numbers (set)	Ratio of internal and boundary crossing fluxes	Openness degree of the object against energy, momentum and mass fluxes
Ve	“Velocity-emission”	$\left(\frac{E_{kin}}{E_{at}}\right)\left(\frac{x}{v\tau_{rad}}\right)$	Mass density
Kn	Knuden numbers (set)	λ/x	Length
Fr	Froude	v^2/gl	Gravity
F	Faraday number	$\frac{1}{c}\frac{\partial A}{\partial t}\Big/\nabla\varphi$	Electric fields and charges $\left(\frac{j}{\rho c}\right)\left(\frac{x}{ct}\right)$

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

New interpretation of the classical observation

E. Pettit, The Great Eruptive Prominences of May 29 and July 15, 1919,

***Astrophys. J.*, vol. 50, pp. 206-219, 1919**

Internal and External Motions

Velocity reconnection

Loops and whips

E.Pettit does not addmitted external motions

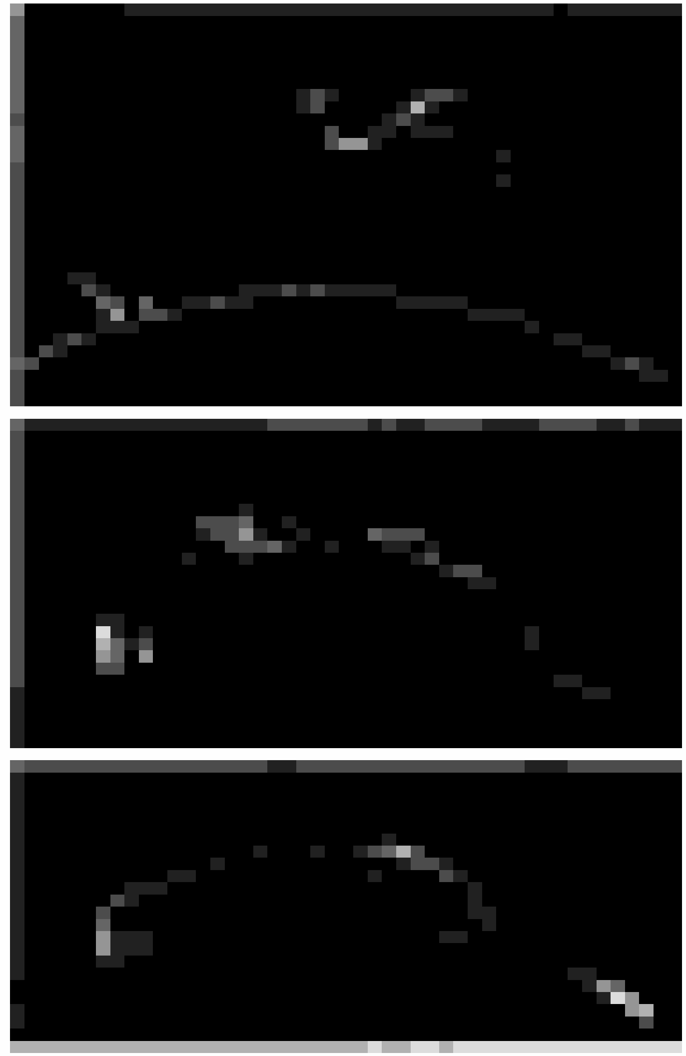
May 15, 1919

huge prominence on the East limb

8 hours rise up to 2 solar radii

stereo couples and velocity tracing

a loop transformed into a whip



Height versus time

Detailed stereoscopic velocity measurements (0 - ~ 100 km/s)

Simple velocity model

siphon flow+solar wind=

whip formation

Strouhal number

- S ~ vt/L **non-invariant, reference frame dependent parameter**
- S>>1 quasi-stationary flow (asymptotically large S values mean steady state)
- S<<1 transient flow
- S~1 intermediate regime (for example, linear waves or small convective perturbations)

Strouhal number (ctnd)

- $S \sim Vt/L$
- Quiescent prominences:
- $L \sim 10^5$ km, $V \sim 1$ km/s, $t \sim 10^6$ s (many days, a month) (life time)
- Hence, $S \sim 10$
- Looks like quasi-steady flows during life time

Strouhal number (ctnd)

- $S \sim vt/L$
- Eruptive prominences: for example,
- $L \sim 10^5$ km, $V \sim 100$ km/s, $t \sim 1$ hour
- Looks like transient phenomenon

Laminar? Turbulent?

- Number of degrees of freedom N involved in process under consideration
- Laminar if N~ 1 “simple”
- Turbulent if N>>1 “complicated”
- Reynolds number Re is not invariant for this purpose (reference frame dependent impressions of flow). Because of this,
- Re >1, Re <1 is not a good classification.

Dimensionless Faraday number F

- Ratio of inductive and potential electric fields
- **F~ (j/ρc) (L/ct)**

where

j - electric current density

ρ - electric charge density

L - length

c - velocity of light

t - time

F>>1 inductive fields dominate

F<<1 Coulomb fields dominate → electrostatics **important!**

Applications: thermonuclear fusion problem, double layers on the Sun

Trieste numbers T

- Set of dimensionless parameters: ratios of energy, momentum , mass fluxes inside, outside and across the volume boundaries
- T>>1 open system
- T<<1 closed system
- T~1 intermediate case
- **Important example:** quiescent prominence – open system with mass flows through it (siphon flows in loops from one foot point to opposite foot point, blue and red shifts in legs). It is not a magneto-static equilibrium (as generally believed) but a quasi-steady or non-steady state with flows

Why solar flares and CMEs originate?

- It is because of subphotospheric free energy supply in the same, larger and smaller space-time scales: $T \sim 1$, $T \gg 1$, $T \ll 1$.
- All these regimes involved in preparation and development
- They are non-linearly coupled

- Information and 'signals' from interior of the Sun are needed to predict solar flares and CMEs

Ve number (on the Sun)

- Ratio of the energy losses via solar wind to the losses due to electromagnetic radiation of the corona
- Averages on time :
- Ve>>1 in coronal holes (dark regions, fast wind)
- Ve<<1 in active regions (bright loops, slow motions)
- Ve~1 intermediate value in quiet corona

Ve number (continued)

- Ve>>1 in coronal mass ejections (CMEs) – high loop eruptions, prominences, arcades
- Ve<<1 in solar flares – low loops, brightening, confined motions
- Ve~1 intermediate case - both
- Typically CMEs and flares are accompanying each other in different proportions from CME-like to flare like situations
- Flares/CMEs: No cause/consequence relations, but parallel energy release channels from the same free energy sources

Syrovatsky number

- Defined as combination M^2/M_A.
- Includes temperature, magnetic field, velocity
- NOT INCLUDES DENSITY!

Comfortable for the classification of incompressible MHD flows

- The same $M\ \beta^{-1/2}$
- The same $M_A\beta^{-1}$
- Here $\beta \sim (M_A/M)^2$.
  P/B^2

CONCLUSIONS

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