CORONAL MASS EJECTIONS AND THE CRITICAL VELOCITY IONIZATION PHENOMENON

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Abstract. We propose a new viewpoint concerning the mechanism for coronal mass ejection (CME) formation in the solar corona. According to developed approach the origin of CME is connected with high-speed movement in the transition zone or lower. The high-speed flows of neutral gas are able to produce explosive events (EEs) and jets in the chromosphere by the critical ionization velocity (CIV) mechanism. They can be sources of eruptive prominences. In this case CIV phenomenon results in ion and electron heating up to tens of eV. In turn high-energy electrons can cause weak flares. The eruptive prominences generate CMEs with velocities $\geq$ 100 km s^{-1}. Thus, the following chain of phenomena appears to form the observed CME: high-speed movements of neutral gas – its ionization due to CIV phenomenon – eruptive prominences (weak flares) – CMEs.

Key words: CME – High Speed Flows

1. Introduction to the Critical Ionization Velocity Mechanism

The CIV mechanism was introduced by Alfvén (1954) in his theory of the solar system origin. Alfvén postulated that rapid ionization of neutral gas occurs, when it moves through magnetized plasma with velocity V_0, whose component perpendicular to the magnetic field exceeds a critical value

$$V_{0\perp} \geq V_c = \sqrt{2\chi_i/m_n}, \tag{1}$$

where χ_i and m_n are the ionization energy and mass of the neutral particle, respectively.

Experimental and theoretical studies of CIV have shown that the process occurs if the following conditions are met:

1) The velocity $V_{0\perp}$ of neutral particles relative to the magnetized plasma must be higher than critical velocity

$$V_{0\perp} > V_c \tag{2}$$

2) Ratio of Alfvén velocity V_A in the background plasma to $V_{0\perp}$ is more than unity

$$V_A/V_{0\perp} > 1 \tag{3}$$

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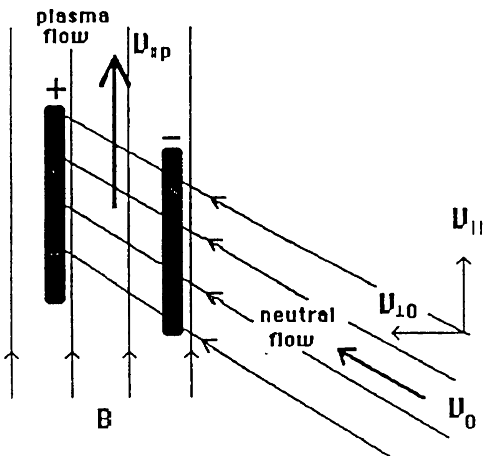

Figure 1. Illustration of the problem.

3) The Taundsen condition. The integrated neutral density along the flow into the plasma must be sufficiently high that electrons can ionize atoms during their passage through the plasma

$$\int N_n dx > V_c / < \sigma_{ion} V_e > \tag{4}$$

where $< \sigma_{ion} V_e >$ is a maximum volume ionization rate, and σ_{ion} is the ionization cross-section for electron - neutral collisions. This condition plays a crucial role in the experiments that were carried out in the Earth's upper atmosphere. Low ionization in artificial clouds (less than 8%) in these experiments is, probably, connected with the decrease of neutral particles density in the clouds (Lai *et al.*, 1992).

4) The free energy for CIV is provided by the perpendicular-to-B motion of neutral particles relative to the plasma. The component of the plasma bulk speed that is perpendicular to the magnetic field is defined by electric drift. Hence, relative-to-plasma velocity of neutral gas flow is

$$V_1 = \left| \boldsymbol{V}_{0\perp} - c \left[\boldsymbol{E} \times \boldsymbol{B} \right] / B^2 \right| , \tag{5}$$

where $\boldsymbol{E}$ is an electric field generated by the neutral flow. With $V_1 > V_c$ electrons get enough energy to ionize neutral particles. The four above conditions define CIV occurrence in the system where high-speed neutral flow enters the magnetized plasma.

2. High-Speed Plasma Flow Generation in the Solar Atmosphere

Let the flow of neutral particles (hydrogen) move in the solar atmosphere at the boundary of a magnetic field $B = 15$ G with $V_{0\perp} = 100 \text{ km s}^{-1}$. The altitude H of the plasma flow generation can be found in this case. Assume that $\nu_{ion}/\Omega_+ > \sqrt{M_e/M_i}$, where

$$\nu_{ion} = N_n < \sigma_{ion} V_e > \approx 0.04 N_n \sqrt{T}_e \tag{6}$$

where σ_{ion} is taken from Anders (1990) and T_e is the electron temperature. For $T_e = 12.5$ eV we have $N_n > 2\times 10^{10}$ cm^{-3} from the condition $\nu_{ion}/\Omega_+ > \sqrt{M_e/M_i})$. H decreases as the magnetic field increases.The Taundsen condition (4) is also realized for these parameters of neutral flow and ambient plasma. Maximum density of the ambient plasma N_0 is constrained by inequality (3). We can rewrite this expression as $V_{0\perp}\sqrt{4\pi N_0 M_h}/B < 1$ where M_h is the mass of a hydrogen atom. So we get an upper boundary for N_0 as $N_0 < 10^{11}$ cm^{-3} for $B = 15$ G.

To estimate V_1 in eq. (5) consider the following simple model. The cross section of ion-neutral collision is for hydrogen plasma about $\sigma_{in} = 4 \times 10^{-15}$ cm^2 (Anders, 1990). Then the ion-neutral collision frequency is $\nu_{in} = N_n < \nu_{in} V_i >\approx 4.4 \times 10^{-8} N_n$, that is less than Ω_+, i.e. $\Omega_+/\nu_{in} >> 1$. In this case we get for the perpendicular current an estimate

$$\boldsymbol{j} = \sigma_{ped}(\boldsymbol{E} + (\boldsymbol{V}/c) \times \boldsymbol{B}), \tag{7}$$

where $\sigma_{ped} = c^2 N_0 M_h \nu_{in}/B^2$ is Pedersen conductivity for $\Omega_+/\nu_{in} >> 1$ and $V = V_{0\perp}$. From Maxwell's equations and (7) we get $curlcurl\boldsymbol{E} = -\frac{1}{c}\frac{\partial}{\partial t}(4\pi \boldsymbol{j}/c)$, or estimating $\mid \boldsymbol{E} \mid= 4\pi h^2 \sigma_p ed/c^2 \tau \mid \boldsymbol{E} + (\boldsymbol{V}/c) \times \boldsymbol{B} \mid= \gamma \mid \boldsymbol{E} + (\boldsymbol{V}/c) \times \boldsymbol{B} \mid$, where h and τ are characteristic length and time for CIV, respectively. If $h \approx \rho_i = V_{0\perp}/\Omega_+$ (ρ_i is a Larmor radius of ions) and $\tau \sim \Omega_+^{-1}$ then $\gamma \approx (V_{0\perp})^2 \nu_{in}/(V_a)^2 \Omega_+ << 1$ and $c \mid \boldsymbol{E} + (\boldsymbol{V}/c) \times \boldsymbol{B} \mid << V_{0\perp}$.

Thus, the conditions for CIV realization determine region in the solar atmosphere where plasma flows can nucleate. This region lies at the height $\sim$ (1,000 $\div$ 1,500) km in the lower chromosphere for $B = 15$ G. High-speed flows of plasmas and neutral particles have been discovered and studied in the solar chromosphere by HRTS and Spacelab 2 (Brueckner and Bartoe, 1983; Dere *et al.*, 1989). Turbulent events and jets were investigated by Doppler shift of the lines of ionized Si and C. Also jets in hydrogen Lyα have been discovered in those experiments. Dere *et al.* (1989) have shown that jets in the solar atmosphere are very rare phenomena and turbulent events with dominant blue wings outnumber the events with dominant red wings about 3:2. Therefore, those phenomena have been renamed as EEs. Thus we can assume that at the height $\sim$ 1,000 km the flows of the neutral hydrogen generate plasma flows in the magnetic field by the CIV phenomenon. The height of such generating depends on the parameter values of the neutral flow, ambient plasma and the magnetic field. It is 1,000 km for $B = 15$ G and decreases as the magnetic field increases. This conforms to the jet and the EE initiation heights measured by HSTR and Spacelab 2 (Dere *et al.*, 1989). Thus, CIV phenomenon appears to play crucial role in the generation of the high-speed plasma flow in the solar atmosphere. Such a flow can be among sources of prominences and EEs in the chromosphere.

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