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Magnetic Reconnection Model for the Driven Mechanism of Jets above Thunderclouds

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Abstract: *It has been discovered that jets above thunderclouds are the unusual and large-scale transient luminous electrical discharges events. A magnetic reconnection model is developed to explain the driven mechanism of jets above thunderclouds. Based on this model the basic properties of the blue jets, such as lifetime and velocity, are obtained. They are consistent with the observations. It indicates that the formation of jets above thunderclouds is probably driven by the magnetic reconnection.*

Keywords: *Jets; Magnetic reconnection; Lightning; Thunderclouds*
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I. Introduction

The phenomena of unusual large-scale luminous optical discharges above thunderclouds have been reported for over a century[1]. Blue jets[2], blue starters[3] and gigantic jets[4-6] are the transient luminous electrical discharges (TLED) events above thunderclouds. These surprising TLED phenomena have been studied extensively in past decades. During the Sprites 1994 aircraft campaign, scientists from the Alaska University had captured the first images of blue jets and blue starters[7] which are termed by Wescott. Observations in the past decades have revealed that blue jets have the following typical characteristics[1,2,8-11]: They are narrowly collimated beams of blue light with a few kilometers wide, they propagate from the upper boundary of active thunderclouds(~18km) to the top stratosphere(~40km) with a vertical velocity ~100km/s, they happened occasionally with a lifetime ~200-300ms.

So far, several models for the jets have been proposed. Such as, (1) the mechanism of the conventional air breakdown suggested that jets are either gigantic positive streamers[8] or negative streamers[12]; (2) the mechanism of relativistic runaway air breakdown is put forwarded by Roussel-Dupre[13] and Taranenko[14]; (3) the fractal model[1,15] and the optical emission model[1] of the jets; (4) the two-leader streamers model[16]. These models are excellent interpret some characteristics of the jets, but no theory has yet accounted for all jet characteristics[1,9]. Many questions still remain opening, e.g., the relation between the blue jets and cloud-to-ground or cloud-to-cloud lightning activity, the driven force for the breakout of jets, and the lifetime of blue jets. The kinetic driven is the most important factor, it determines the intrinsic characteristics of jets.

Jets above thunderclouds are an explosive phenomenon in the stratosphere[9], and an important ingredient for the global electrical circuit system of earth[8,17]. The typical characteristics of jets above thunderclouds are similar to those explosive phenomenon caused by magnetic reconnection in the solar corona[18−21], the magnetotail[22], the Earth's magnetosphere[23] and laser plasma[24−26]. Reconnection of magnetic fields in plasma are important fundamental processes with implications for wide range of basic science [27], including astrophysics, space physics, and laboratory physics. Considering that, this paper try to reveal the kinetic driven of blue jets, based on the magnetic reconnection model. Through the theoretical analysis and considering the physical conditions of the thunderstorms, the velocity and lifetime of blue jets have obtained. And it is well coincided with the observations. That means, magnetic reconnection is a possible driven mechanism for the jets above thunderclouds.

This paper is organized as follows, the magnetic reconnection model of driven mechanism of jets above thunderclouds is analyzed in Sec.2, basic theory for magnetic reconnection process is present in Sec.3; computation results are obtained in Sec.4; followed by some conclusions are given in Sec.5.

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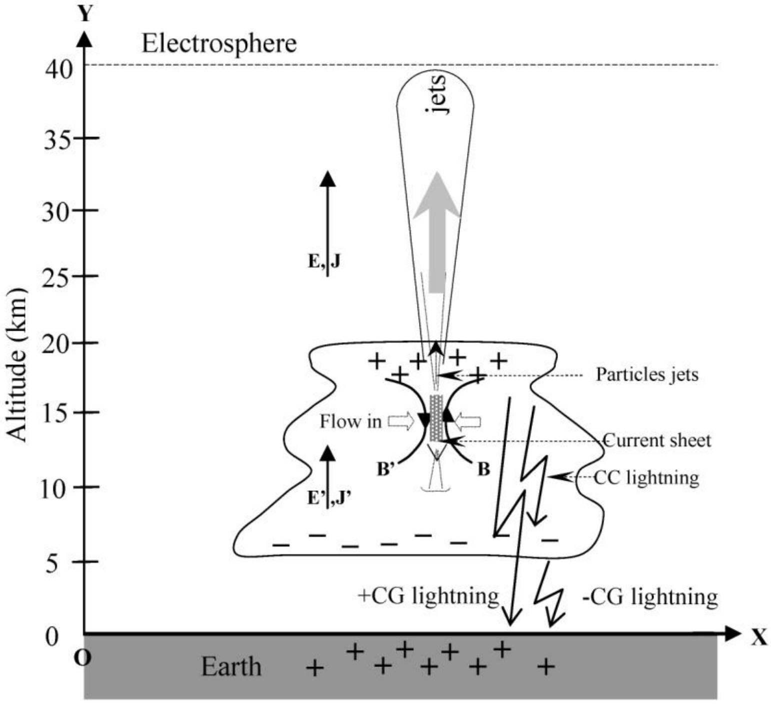

Figure 1. The schematic diagram of the jets, including current, charge, electric fields and the likely topology of magnetic fields in the thunderstorms.

II. The model of driven mechanism of jets above thunderclouds

Based on the typical characteristics of jets above thunderclouds, we regard driven force of jets above thunderclouds as a result of the local explosive instability caused by magnetic reconnection; and we inferred that jets are strongly related to cloud-to-ground (including positive and negative CG) or cloud-to-cloud (CC) lightning flashes[5] through magnetic fields. In the active thunderstorms, large-scale charge flow, CG and CC flashes events are very frequent. Meanwhile, the induced electromagnetic field and transverse plasmons are abundant. Moreover, the recent observations[4,5] has referred to the magnetic field which has been detected in the direction of the blue jets. Therefore, in the thunderclouds, there likely exists the self-generated magnetic field with configuration as shown in Fig.1. The magnetic reconnection, which driven by ponderomotiove force resulted from transverse plasmons, may take place in the intermediate vicinity of the X-point[28]. In this case, the plasma and magnetic flux, which are driven by a Lorentz force, can be compressed toward the current sheet from both sides, leading to a resistive instability. During the process, the magnetic field is annihilated, and the magnetic energy is partly converted into the kinetic energy of particles, followed by enhanced transverse plasmons occurring in the current sheet. Then the particles are accelerated and ejected out from the current sheet, and two collimated particles jets are formed[29,30]. These particles jets, which is essential for the formation of jets above thunderclouds, act as the trigger of the discharge process.

For the physical features of the thunderclouds, the upward energetic particles jet (including the charged particles and neutral particles) is possibly ejected out from the thunderclouds, only when the electric current sheet, located in the upper boundary of thunderclouds, has released enough energy. Otherwise, the energy of the particles may be completely dissipated before leaving the thunderclouds. That is to say, only the jet located on the top of thunderclouds may be emerged more easily. The high-speed charged particles, together with the breakdown air stimulated by energetic particles, form a conductive channel. The narrowly collimated channel extends upwards from the upper boundary of thunderclouds to the stratosphere. Meanwhile the large amount of accumulated charge in the top of thundercloud is quickly discharged the along channel. Then a large-scale discharge luminous optical jets above thunderclouds will be captured. Depending on the process of magnetic reconnection, the velocity and lifetime of jets can be obtained. On the other hand, the followed terminal altitude and other observed properties of jets above thunderclouds are depend on the physical conditions of the thunderclouds, that were good interpreted by many works[1-16]. In a sense, the upward particles jet generated by magnetic reconnection act as a wire, connecting the thundercloud and stratosphere. Thus, a global electrical circuit system is formed by earth, lightning, thunderclouds, jets and stratosphere.

III. The Magnetic Reconnection Process

As suggested above, it appears that there is a magnetic configuration with parallel and anti-parallel components, as shown in Fig.1, so that the process of magnetic reconnection occurs. According to reconnection theory, the thickness of the dissipation layer must remain at very small value in order to provide sufficient power; however, the hot plasma, resulting from magnetic field dissipation, will tend to widen the current sheet[30]. The key is to find a local explosive instability for which dissipation products can be thrown out at a fast-enough rate. Of course, instability with a small scale inevitably involves a nonlinear interaction between the transverse plasmons and the magneto-hydro-dynamics (MHD) media. For thunderstorms plasma with electromagnetic oscillations, we use a two-fluid (electron, ion) description to analyse the driven process of blue jets. Because of the large difference in electron and ion oscillations in a thunderstorm's plasma, the two-time-scale approximation is also relevant. In such a case, the dynamics for electrons and ions are described by[19,30]

$$\frac{\partial n_e}{\partial t} + \nabla \cdot (n_e \mathbf{v}_e) = 0, \tag{1}$$

$$\frac{\partial n_{zi}}{\partial t} + \nabla \cdot (n_{zi} \mathbf{v}_i) = 0, \tag{2}$$

$$\frac{\partial \mathbf{v}_e}{\partial t} + (\mathbf{v}_e \cdot \nabla)\mathbf{v}_e = \frac{e}{m_e}(\mathbf{E} + \frac{1}{c}\mathbf{v}_e \times \mathbf{B}) - \frac{\nabla P_e}{m_e n_e}, \tag{3}$$

$$\frac{\partial \mathbf{v}_i}{\partial t} + (\mathbf{v}_i \cdot \nabla)\mathbf{v}_i = \frac{-Ze}{m_{zi}}(\mathbf{E} + \frac{1}{c}\mathbf{v}_i \times \mathbf{B}) - \frac{\nabla P_i}{m_{zi} n_{zi}}, \tag{4}$$

$$\nabla \times \mathbf{B} = -\frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} + \frac{4\pi}{c}(en_e \mathbf{v}_e - Zen_{zi}\mathbf{v}_i), \tag{5}$$

$$\nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}, \tag{6}$$

$$\nabla \cdot \mathbf{B} = 0, \tag{7}$$

where $\mathbf{v}$, P, $\mathbf{E}$, $\mathbf{B}$, Z, n_e, n_{zi} and m_{zi} are the velocity, thermal pressure, electric field, magnetic field, the ion charge state, electron density, ion density and ion mass, respectively; and the subscripts e and i show the electron and ion components.

Based on the two time-scale approximation, all the field quantities could be divided into the fast time-scale and slow time-scale component:

$$A = (n_e, n_{zi}; \mathbf{v}_e, \mathbf{v}_i; P_e, P_i; \mathbf{E}, \mathbf{B}) = A_f + A_s. \tag{8}$$

And it could be assumed that the ensemble average value of fast time-scale components over the slow time-scale vanishes:

$$< A_f >= 0. \tag{9}$$

On a slow time-scale, a quasi-neutrality condition is valid:

$$< en_e - Zen_{zi} >= 0. \tag{10}$$

For the thunderstorms plasma the result is

$$n_{e_s} = Zn_{zi_s} \equiv n_s. \tag{11}$$

Defining

$$\rho = n_s(m_{zi} / Z + m_e), \tag{12}$$

$$\mathbf{u} = (\frac{m_{zi}}{Z}\mathbf{v}_s^i + m_e \mathbf{v}_s^e)/(\frac{m_{zi}}{Z} + m_e). \tag{13}$$

For convenience, we marked $m_i = \frac{m_{zi}}{Z}$ and ignored the subscripts s in the following text. Similar to the analysis in references[18,19,31], from Eqs. (1)-(7), on the slow time-scale, it is straightforward to obtain a set of equation for global coupling MHD equations with ponderomotive force:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0, \tag{14}$$

$$\rho\left[\frac{\partial \mathbf{u}}{\partial t}+\left(\mathbf{u}\cdot\nabla\right)\ \mathbf{u}\right]=\frac{1}{4\pi}(\nabla\times\mathbf{B})\times\mathbf{B}-\nabla P+\mathbf{F}_p, \quad (15)$$

$$\frac{\partial \mathbf{B}}{\partial t}=\nabla\times(\mathbf{u}\times\mathbf{B})+\frac{c^2}{4\pi}\eta\nabla^2\mathbf{B}, \quad (16)$$

$$\nabla\times\nabla\times\mathbf{v}_f+\frac{1}{c^2}\frac{\partial^2\mathbf{v}_f}{\partial t^2}+\frac{1}{c^2}\frac{4\pi e^2}{m_e}n_e\mathbf{v}_f=0, \quad (17)$$

$$\nabla\times\mathbf{B}=\frac{4\pi}{c}\mathbf{J}, \quad (18)$$

$$\nabla\times\mathbf{E}=-\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}, \quad (19)$$

$$\nabla\cdot\mathbf{B}=0, \quad (20)$$

where $\mathbf{F}_p=-\frac{1}{2}\frac{m_e}{m_i}\rho\nabla\left\langle \mathrm{v}_f^2\right\rangle$ is the ponderomotive force, v_f is the fast oscillation velocity of the electron in the wave fields. And the generalized ohm law is $\mathbf{J}=\sigma(\mathbf{E}+\frac{1}{c}\mathbf{u}\times\mathbf{B})$, $\sigma=\frac{n_e e^2}{m_e(\nu_{ei}+\nu_{en})}$, and $\eta=1/\sigma$ is the electric resistivity; where ν_{ei} and ν_{en} are the electron-ion and electron-neutral collision frequency.

For convenience, we shall perform an incompressible analysis, which can be justified in the most physical region[32]. The motion of plasma is along the **x**-direction, and the unperturbed field is B_{0y} perpendicular to the **x**-direction. First let us examine the steady state:

$$\mathbf{u}_0=0,\ \ \rho_0=\bar{\rho}_0+\rho_{01}(x),$$

$$\mathbf{B}_0=B_{0y}(x)\mathbf{e}_y=\bar{B}\tanh\left(\frac{x}{L_s}\right)\mathbf{e}_y.$$

Within the current sheet (i.e., $|x|\in|x/L_s|=\ 1$), the magnetic field can be approximated by

$$\mathbf{B}_0=\bar{B}\frac{x}{L_s}\mathbf{e}_y.$$

Due to the repellent of the ponderomotive force, the density within the current sheet is [31]:

$$\rho_{01}(x)\approx-\frac{1}{c_s^2}\frac{\mu\bar{\rho}}{4}\bar{v}_0^2\sec h^2\left(\frac{x}{\varepsilon_0}\right),\ (\mu=m_e/m_i),$$

here c_s is the speed of sound, $\bar{v}_0$ is the amplitude of the fast oscillation $\mathbf{V}_{f0}$,

$$\mathbf{V}_{f0}=\frac{1}{2}\left[\mathbf{v}_0 e^{i\omega_{pe}t}+c.c.\right],(\omega_{pe}^2=\frac{4\pi n_e e^2}{m_e}),$$

ε_0 is the width of the solitary wave:

$$\varepsilon_0=\left(\sqrt{8}/\sqrt{\mu}\right)\ \left(\frac{c}{\omega_{pe}}\right)\ \left(c_s/\bar{v}_0\right). \quad (21)$$

We can see from the above that the ponderomotive force by transverse plasma waves excludes plasma, leading to diminishing the density within the current sheet.

Examining the perturbation state in the form

$$A(x,y,t)=(u_x,B_x)=A(x)e^{ik_y y}e^{\gamma t},$$

then from Equations (14) to (21) we obtain

$$\psi''=\alpha^2\psi(1+\gamma\tau_R/\alpha^2)-ik_y\tau_R F u_x, \quad (22)$$

$$(\theta_0 u_x')'=\alpha^2 u_x[\theta_0+\tfrac{S^2}{\gamma^2\tau_R^2}G_0+\tfrac{S^2}{\gamma\tau_R}F^2]+\tfrac{i}{k_y\tau_R}\psi\alpha^2 S^2(F-\tfrac{F''}{\gamma\tau_R}), \quad (23)$$

where

$$\psi = B_x / \bar{B}, \ \ \theta_0 = \rho_0 / \bar{\rho}_0, \ \ S = \tau_R / \tau_H ,$$
$$\tau_H = 4\pi L_s \sqrt{\bar{\rho}_0} / \bar{B}_0, \ \ \tau_R = 4\pi L_s^2 /(\eta c^2), \tag{24}$$
$$F = B_{0y} / \bar{B}_0, \ \ \alpha = k_y L_s, \ \ \bar{x} = x / L_s;$$

and

$$G_0 = (-\frac{1}{4}\mu \frac{d}{dx}\left|\mathbf{v}_0\right|^2)\frac{\rho_0}{\bar{\rho}_0}\tau_H^2, \tag{25}$$

$$\left|\mathbf{v}_0\right|^2 = v_0^2 \sec h^2(\sqrt{\frac{\mu}{8}}\frac{v_0}{c_s}\frac{\omega_{pe}}{c}x), \tag{26}$$

where the superscript prime represents the derivative with respect to $\bar{x}$. In the absence of transverse plasma waves, i.e. $G_0 = 0$, Equations (22) and (23) are reduced to those discussed by Furth *et al.*[32].

Outside the current sheet ($\eta \to 0$), the solution for Equations (22) and (23) is[31]

$$\psi = ikFu_x / \gamma, \tag{27}$$

$$\psi_{\pm} = \{ \begin{matrix} e^{-\alpha\bar{x}}[1+(\tanh\bar{x})/\alpha], & \bar{x} > 0 \\ e^{\alpha\bar{x}}[1-(\tanh\bar{x})/\alpha], & \bar{x} < 0 \end{matrix} \tag{28}$$

using the incompressible condition yields from Equation (27) and (28),

$$u_y(x) = -\frac{\gamma}{k_y^2 L_s}\frac{1}{\bar{x}^2}, \ \ (\bar{x} = \ \ 1);$$

Then the average value over the current sheet scale L_s is

$$\bar{u}_y(x) = \frac{1}{L_s}\int_{-L_s/2}^{L_s/2} u_y(\bar{x})d\bar{x} = \frac{4\gamma}{k_y^2 L_s}. \tag{29}$$

And one obtains the jump condition across the sheet in the outer region:

$$\Delta' = (\psi'_{+0} - \psi'_{-0}) / \psi(0) = 2(\alpha^{-1} - \alpha).$$

On the other hand, under a constant ψ_0 approximation, one can get the jump condition within the current sheet in a similar way given by Furth *et. al.*[32]. From two jump conditions, one has[19]

$$4\pi\frac{(\gamma\tau_R)^{5/4}\Gamma(\frac{3}{4})}{(\alpha S)^{1/2}\Gamma(\frac{1}{4})}(1+\zeta)^{1/4} = 2(\alpha^{-1} - \alpha). \tag{30}$$

with

$$\zeta = d_0^2 /(\gamma\tau_R), \ \ d_0^2 = \pi\mu^2(\frac{\bar{v}_0}{c_s})^2(\frac{\bar{v}_0}{\bar{v}_A})^2(\frac{L_s}{\varepsilon_0})^4, \tag{31}$$

where Γ is the gamma function and $\bar{v}_A$ is the Alfven velocity. Equation (30) is the key equation for determining the resistive instability by solitary waves (ζ ? 1), and the growth rate of this instability can be deduced from equation (30) in the form:

$$\gamma \approx \frac{1}{d_0^{1/2}}\frac{(\alpha S)^{1/2}(\alpha^{-1} - \alpha)}{2\pi}\frac{\Gamma(\frac{1}{4})}{\Gamma(\frac{3}{4})}\frac{1}{\tau_R}(s^{-1}). \tag{32}$$

In addition, the plasma waves near the current sheet can scatter the current-carrying electrons, there is an anomalous resistivity. But here the scatter is much lower than the ordinary Coulomb collisions of plasma particles, so here we do not include this effect. In the next analysis, we will adopt the typical parameters of thunderstorms with equations (29) and (32) to discuss the characteristics of blue jets.

IV. Computation Results And Discussion For Typical Jets

For transverse plasmons have a dispersion relation similar to the one of the Langmuir plasmons, the interactions among wave-wave and wave-particle will lead to the tendency of equipartition of energy over both the Langmuir and transverse plasmons. Then one has[18]: $\bar{W}^p = \left(\frac{E_f^2}{8\pi}\right)/(n_e k_B T_e) \ge N_D^{-1} = \frac{\omega_{pe}^3}{n_e v_{Te}^3}$. Using the momentum equation with the lowest order $\frac{\partial \mathbf{v}_f}{\partial t} \approx \frac{e}{m_e}\mathbf{E}_f$, yields $\bar{W}^p \approx \frac{(v_f^0)^2}{2v_{Te}^2} = \frac{(\bar{v}_0)^2}{4v_{Te}^2} \geq N_D^{-1}$. Hence, with a large reserve, one may take $\bar{v}_0 = \sqrt{4v_{Te}^2 N_D^{-1}}$.

In the thunderclouds, the temperature, electron and neutral density in the region (around at 17 km) roughly are $T_e = 3000K$, $n_e = 10^{13} cm^{-3}$ and $n_n = 10^{18} cm^{-3}$, respectively[16]. According to the Ampere's law $\oint \mathbf{B} \cdot d\mathbf{L} = \frac{4\pi}{c} I$, in the current sheet, conservative estimate the self-generated magnetic field is $B = 0.03 Gauss$. If we take ion to be the proton and $Z = 1$. The collision frequency between the electrons and ions is $\nu_{ei} \approx \omega_{pe} / N_D = 3.0 \times 10^{12} s^{-1}$ and the collision frequency between the electrons and neutrals is $\nu_{en} = n_n \sigma v_{Te} \approx n_n (5 \cdot 10^{-15}) v_{Te} = 1.1 \times 10^{11} s^{-1}$. Then we have $\bar{v}_0 = 1.0 \times 10^7 cm/s$ and $\eta = 1.25 \times 10^{-9} s$. And if we use $\pi / k_y = L_E = 350m$ and $L_s = 2m$ (L_E and L_s are the typical scale for blue jets' root), from equations (29) and (32), we obtain the lifetime and the velocity of blue jets are

$$\tau \approx \gamma^{-1} = 230ms$$

and

$$\bar{u}_y = 110 km/s,$$

which are consistent with the observations of typical blue jets. Furthermore, the estimated energy ε released from the interaction region of magnetic reconnection is as follows[19]: $\varepsilon = \frac{c^2}{4\pi^2} \eta \frac{B^2}{D} \cdot \bar{A} \cdot \tau$, where $\bar{A} \approx L_E \times L_s = 7.0 \times 10^6 cm^2$ is the area of interaction region , D is the thickness of the current sheet. With a large reserve, take $D \approx 20cm$, one may obtain the released energy is $\varepsilon = 3.5 \times 10^{14} erg$.

V. Conclusions

The magnetic reconnection model for the driven mechanism of jets above thunderclouds is studied. During the coalescence of multiple magnetic loops, the plasma and magnetic flux may be compressed toward the current sheet from both sides, driven by a Lorentz force, leading to a resistive instability. Followed by enhanced transverse plasmons occurring in the current sheet, the topological rearrangement of magnetic field lines forms a new equilibrium configuration of lower magnetic energy, and the conversion of magnetic energy to the kinetic energy of particles, thermal energy of the plasma, resulting in the formation of collimated particles jets. The upwards particles jets are likely to form a conductive channel from thunderclouds to the stratosphere. Consequently, the upward discharge is happened along the channel. Then a large-scale discharge luminous optical jets above thunderclouds is formed.

In this model, the explosive of jets above thunderclouds is closely related to the lightning in the thunderstorms. And the velocity and lifetime of blue jets are determined by Equations (29) and (32). The consistency of computation results with the observational data indicates that the phenomenon of blue jets may be driven by magnetic reconnection.

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