ON THE VISIBLE SHAPE OF THE COLD PLASMA JETS IN THE
SOLAR CHROMOSPHERE

I. S. VESELOVSKY
Institute of Nuclear Physics, Moscow State University, 119899, Russia

L. TŘÍSKOVÁ
Geophysical Institute, Czech Academy of Sciences, 141 31 Praha 4, Czech Republic

and

S. KOUTCHMY
Institut d’Astrophysique de Paris, CNRS, 98 bis Boulevard Arago, F-75014, France

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Abstract. Lines of equal optical thickness are calculated for cold plasma jets propagating in the
simplest magnetic configuration. The paraxial approximation is used in the case of jets directed along
the axis of a magnetic dipole. The results explain the apparently convergent as well as divergent
shapes of the jets in a divergent magnetic configuration.

1. Introduction

Recent high-resolution CCD observations of solar spicules (Koutchmy and Lorrain, 1992) indicate that individual components of spicules (jets) have a diameter of
0.2 Mm or less and aspect ratios of 20 or more. Some spicules are curved, but most
are straight. The acceleration phase in the first Mm takes place in less than 30 s.
The apparent velocity of the cold ‘head’ can be as large as 50–100 km s\(^{-1}\) during
the impulsive phase. After this the head velocity first decreases and then reverses
during most of the spicules lifetime. Before the end of the acceleration phase, a
second component occasionally appears with typically the same behavior. After
two or three minutes one sees either two or more thin quasiparallel straight threads.

A tentative model of impulsive ejection phenomena comprising a hot jet-like core with a cold component in a partially ionized plasma was proposed to
explain some of these features, but many problems remain (Koutchmy and Lorrain, 1992). The spicules are probably stretched out along magnetic field lines
(Priest, 1982). The local plasma parameters and the electrodynamical conditions
are poorly known. The lack of essential experimental information does not permit
the construction of reliable quantitative models. The uncertainty about models of
spicules is illustrated by Beckers (1977) in his Figures 4.1a and 4.1b representing
cold (a) and hot (b) models. The difficulties with determining the ionization
degree, optical thickness and other quantitative characteristics about solar spicules
and prominences are well known. For example, justification of the approxima-
tions and estimates of radiation transfer corrections are needed to calculate neutral
atom densities using simultaneous continuum and H\({\alpha}\) intensity observations (see,
e.g., formula (2) in the paper of Koutchmy and Nikolskij (1981)). Another important question is the relation between visible shapes (integrated along the line of sight) and the true geometry. Some kind of inverse problem (integro-differential equations) should be solved to answer this question in the general case.

The purpose of this paper is just to consider the apparent shape of the jets. This shape depends on the magnetic field line geometry, governing the flow, but the relation is 'integral'. The divergent as well as convergent shapes of the bright cores of the jets may appear as a result of a purely geometrical effect of the integration along the line of sight across a divergent magnetic field tube. Some similarity exists with the formation of a burning candle flame shape.

2. A Simple Illustrative Model: Paraxial Jet in a Divergent Magnetic Field

Let us consider a cold (low-β) plasma jet streaming with a constant velocity along magnetic field lines. The cylindrical geometry of the problem is shown in Figure 1. We consider the simplest case of thin axially-symmetric jets near the polar axis of a magnetic dipole (r ≪ z). Paraxial field lines are given in this case by the formula

$$ r = z^{3/2} r_e^{-1/2}, $$

where $r/z \approx (z/r_e)^{1/2} \ll 1$, r and z are cylindrical coordinates with the z-axis directed along the dipole, $r_e$ is the equatorial distance of a dipole field line. Equation (1) is an approximate form of the precise dipole field line

$$ (z^2 + r^2)^{3/2} = r_e r^2. $$

The steady-state continuity equation has the form

$$ F = \pi n(z) v(z) a^2(z) = \text{constant} $$

for a jet flow with constant velocity $v(z) = v$ inside the magnetic field tube with a cross section

$$ S = \pi a^2(z) = \pi a^2 \left( \frac{z}{h} \right)^3, $$

where

$$ a(z) = a \left( \frac{z}{h} \right)^{3/2} $$

is the radius of the magnetic field tube.

The density is obtained using Equation (3):

$$ n(z) = \frac{F}{\pi v a^2} = n_a \zeta^{-3}, $$

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Fig. 1. The axially-symmetric geometry of streamlines and the cylindrical coordinate system \((z, r)\) of the thin paraxial plasma jet streaming along divergent magnetic field lines. The magnetic field is represented by the point magnetic dipole placed vertically at the depth \(h\) \((z = r = 0)\) under the photospheric level. Field lines are described by Equation (1). Boundary conditions for the jet are given at the photospheric level \(z = h\). The simplest case is characterized by the constant form factor (7) of the jet with a given radius \(r(h) = a\) at the photospheric level.

where \(n_a = \frac{F}{\pi va^2}\) is the density of the jet at the top of the photosphere, \(z = h\). We have introduced dimensionless cylindrical coordinates \(\zeta = z/h\), \(\rho = r/h\), \(\varphi\) (see Figure 1). For the sake of simplicity, the form-factor \(n_a\) is supposed to be independent of \(\rho\) and \(\varphi\) inside the radius \(r = a\). Hence, we put a step-like function

\[
n_a = \begin{cases} 
\text{constant}, & \rho < \alpha, \\
0, & \rho > \alpha,
\end{cases}
\]  

(7)

where \(\alpha = a/h\).

For an optically thin jet the optical thickness, \(\tau\), of the individual jet when viewing along the path \(s\) perpendicular to the \(z\)-axis is calculated using Equations (6) and (7). According to the standard definitions (Allen, 1973), one obtains:

\[
\tau(\rho, \zeta) = \sigma \int n \, ds = \tau_a \alpha^{-1} \zeta^{-3} (\alpha^2 \zeta^3 - \rho^2)^{1/2},
\]  

(8)

where \(\sigma\) is the effective cross section of the extinction, and \(\tau_a = 2n_a \sigma a\) is the optical thickness of the central part of the jet at the photospheric level, \(\tau_a = \tau(0, 1)\).
The value of $\tau_a$ may be used as a natural scale of the optical thickness. We introduce the normalized optical thickness $p = \tau / \tau_a$, $p \leq 1$.

The lines of the equal optical thickness $p = \text{constant}$ follow from Equation (8):

$$
\rho = \alpha \zeta^{3/2} (1 - p^2 \zeta^3)^{1/2} .
$$

(9)

Isolines from (9) are shown in Figure 2. Approximations are valid only in the region $\rho \ll \zeta$.

It is clearly seen that isolines are strongly stretched out along the $z$-axis, when the aspect ratio $\alpha^{-1} = h/a \gg 1$. The regions of interest at the level $\zeta > 1$ (over the photosphere) may have needle-like or pencil-like shapes when $\alpha^{-1} \approx 20$, $h \approx 2$ Mm, $a \approx 0, 1$ Mm. Isolines with $p > 1/\sqrt{2}$ are purely convergent at $\zeta > 1$. The top point of the visible jet is given by $\rho = 0, \zeta = p^{-2}$. Hence the visible shape of the jet may be convergent in the case of a divergent flow.

3. An Additional Example: Free Expanding Conical Jet

Let us consider a flow with a constant radial velocity from the point source inside the conical angle $\beta$ (Figure 3).

Lines of equal optical density $\tau = \text{constant}$ when viewing along the path given by coordinates $(r, z)$ of the closest approach of the line of sight perpendicular to the axis are easily obtained by the integration. The result reads as follows:

$$
\tau = 2L (z^2 + r^2)^{-1/2} \arctg \left\{ \frac{[(z \tan \beta)^2 - r^2]}{(z^2 + r^2)^{1/2}} \right\} ,
$$

(10)

where $L = F / \pi v$ is the characteristic scale length, $F = \pi n v (r^2 + z^2)$ = constant represents the mass flux conservation law with the density, $n$, given by the formula

$$
n = \begin{cases} 
\frac{F}{\pi v (r^2 + z^2)} , & r < z \tan \beta , \\
0 , & r > z \tan \beta .
\end{cases}
$$

(11)

In the case of a thin paraxial conical jet ($\beta \ll 1$) the explicit expression for isolines $\tau = \text{constant}$ follows from formula (10):

$$
r \approx \beta z \sqrt{1 - \left( \frac{z}{l_\tau} \right)^2} ,
$$

(12)

where $l_\tau = 2L \beta / \tau$ is the characteristic scale of the isoline with a given optical thickness $\tau$.

The function $r(z)$ as given by Equation (12) describes the visible profile of the thin conical jet ($r \ll z$ for $\beta \ll 1$). The shape of this profile is divergent as $r \approx \beta z$ when $z \approx l_\tau$. The maximum thickness of the profile $r_m = \frac{1}{2} \beta l_\tau$ is obtained at the altitude $z_m = l_\tau / \sqrt{2}$. The apparent top of the jet-like structure is placed at the altitude $z_{\text{max}} = l_\tau$. The shape is divergent when $z < z_m$ and convergent when $z_m < z < z_{\text{max}}$. The curve $r(z)$ is shown in Figure 3 for the case $\beta = 0.25$.  

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Fig. 2. Lines of equal optical thickness of the jet according to Equation (9). Dimensionless coordinates are used. The visible shape of the jet is highly stretched along the z-axis because \( \alpha \ll 1 \). It is convergent in the case of \( p \geq 1/\sqrt{2} \), though the magnetic field line geometry is divergent. The levels \( \zeta < 1 \) are invisible because of the optically thick background.

4. Discussion

We have considered cold plasma jets, quasi-stationary, streaming with a constant velocity along magnetic field lines. We found that convergent or divergent visible shapes are based on the optical thickness calculations of the jets in the case of the simplest divergent field-line geometry.

Dynamical effects have been neglected. Pressure gradients, magnetic stresses, gravity, viscosity and other forces and energy sources may be taken into account (Priest, 1982). Then, quantitative results will change, but the basic qualitative idea about convergent and divergent shapes is of a geometrical nature and does not depend critically on these details and on the magnetic guidance in particular. A comparison of Figures 2 and 3 illustrates this fact.

Time dependence may be parametrically introduced, when parameters \( p(t) \), etc. are changing slowly enough. Rising, stopping, and falling jets may be described this way during the whole time of their evolution, beginning from the initial appearance till the final disappearance. The necessary condition for this assumes that the transit time \( t \sim h \sqrt{p/v} \) will be short in comparison with the characteristic time, \( \tau \), of the source changes, \( t \ll \tau \). Hopefully this condition is satisfied in the case of spicules.

Other types of time dependence are expected in the opposite limit \( t \gg \tau \). The brightness distribution along and across the jets may be modulated by the changes in the source region leading to the formation of connected or disconnected bright
regions. Moving inhomogeneities of these types in the chromosphere are described by Beckers (1977).

Our calculations have been done only for the simplest case of an isolated vertical jet to illustrate the appearance of convergent shapes in divergent flows. Slanted jets are generated by tilted sources. Studying the jets may bring information not only about chromospheric structures but indirectly about subphotospheric processes, electric currents and magnetic fields. More realistic models are needed for these purposes. Multiple jets (chromospheric bushes, wheat field patterns and other morphological structures described by Beckers, 1977) may be generated in the case of more complicated magnetic field geometry or the source function. We do not a priori anticipate the occurrence of opposite polarity fields postulated by Pikel’ner (1969) in his model of spicules. Potential or current carrying magnetic configurations with convergent field lines can help the channeling of the jets, reducing their cross-section. Examples of these configurations are the well-known two- or three-dimensional current carrying streamers and dome-like field lines formed by a magnetic dipole with a superimposed homogeneous field.

Overlapping jets on the line of sight lead to higher optical density in their bottom parts, making them enhanced and confused. Radiation transfer problems are to be solved here and in the optically thick central parts for real brightness calculations of the jets, taking into account the inhomogeneity of the background. Hence, the role of the background is not negligible from observational as well as dynamical
points of view, if we search for the magnetic configuration and the possible drag forces.

Driving forces and energy sources of the jets are only tentatively known. Dissipative and other kinetic processes are poorly understood.

5. Conclusion

Additional observational and theoretical efforts are needed to clarify the kinetic and even the basic MHD parameters and their distribution inside the jets and in the surroundings. This information may help to answer an old question: what are visible chromospheric jets tracing? Laboratory and space plasma physics suggest some possible answers: magnetic field lines, strong local electric currents, electric fields, flow stream lines. There are other possibilities (Alfvén and Fälthammar, 1977) and combinations with density inhomogeneities. In any case, the existence of jets means a lack of equilibrium due to the free energy of large-scale inhomogeneities, non-steady state MHD, or kinetic plasma electrodynamic processes.

We conclude that the visible convergent shape of the jets does not mean automatically the convergence of the flow or a channeling magnetic field with a convergent field line geometry.

References