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Abstract

We draw the attention to filamentary structures in molecular clouds and point out the existence of subfilaments of sinusoidal shape and also of helix-like structures. For two dark clouds, the Lynds 204 complex and the Sandqvist 187-188 complex (The Norma "sword") we make a detailed study of such shapes and in addition we find the possible existence of helices wound around the main filaments. All these features are highly reminiscent of morphologies encountered in solar ascending prominences and in experiments in plasma physics and suggest the existence of electric currents and magnetic fields in these clouds.

On the basis of a generalization of the Bennett pinch model, we derive the magnitudes of the currents expected to flow in the filaments. Values of column densities, magnetic field strengths, and direction of the fields are derived from observations. Magnetic fields with both toroidal and axial components are considered. This study shows that axial currents of the order of a few times 10^{13} A are necessary for the clouds to be in equilibrium. The corresponding mean current densities are very small and even at the very low values of the fractional abundance of electrons encountered in these clouds, the mean electron velocities are of the order of 10^{-2} - 10^{-5} m s⁻¹, much lower than the thermal velocities in the clouds.

We suggest that helical structures may evolve as a result of various instabilities in the pinched clouds. We also call the attention to the kink instability in connection with the sinusoidal shapes. The existence of electromagnetically controlled features in the interstellar clouds can be tested by further observations.

1. Introduction.

Interstellar dust clouds take a variety of forms. The clouds are subject to different internal and external forces which vary in time and space. Because of the sometimes very violent processes that operate in the interstellar medium, one expects a continuous re-modeling of the clouds. Filamentary structures are common. Magnificent examples can be found on high-contrast photographs taken of the Orion nebula and the thin dust clouds at the Pleiades. For the latter, Arny (1977) suggested that the filaments result as a consequence of the radiation pressure from stellar light in a way similar to wind-blown sand on the beach. The formation of filaments, like the so called elephant trunks, through the interaction of shock-fronts on clouds have been subject to several numerical studies (see e.g. Woodward, 1976). These studies show that filaments can form under the conditions assumed.

Magnetic fields penetrate the interstellar clouds. The field-strengths can be estimated from Faraday rotation and Zeeman splitting of for instance lines of H and OH and it is usually assumed that the direction of the electric vector of polarization of light from background stars outlines the direction of the magnetic fields (see e.g. Heiles, 1987 for a review). Typical field strengths measured for dense clouds may amount to 100 μ G. For several elongated clouds the E-vector is perpendicular to the major axis (e.g. Heyer et al., 1987; Tamura et al., 1987). It has been discussed whether contraction preferentially along the magnetic field lines would produce the elongated and sometimes filamentary forms. Such contraction would result in "pancake" forms rather than filaments, however. The presence of molecular cloud clumps lined up along the major axis of the clouds (see e.g. Loren, 1989) and the pattern of cloud extinction indicate that we are observing cylindrical, rather than flat forms .

The magnetic field penetrating the interstellar medium seems to be of non-potential character implying that electric currents must flow in the medium. The currents may arise in many ways and several dynamo mechanisms have been suggested (see e.g. Ruzmaikin et al., 1988). In the present article we draw the attention to complex filamentary structures seen on photographs of nearby molecular clouds. Some of these features are in our opinion highly indicative of the presence of electric currents and in fact, these features have never been "explained" in any way before. In the following, we will also point at some of the consequences of interstellar electric currents.

2. Filamentary structures in two dark clouds.

In order to see whether magnetic fields and electric currents may play an important role in dark molecular clouds we have chosen to study in some detail two clouds of filamentary shape, *viz.* the Lynds 204 complex and the Sandqvist 187-188 complex.

2.1 The Lynds 204 complex

This complex includes several clouds listed by Lynds (1962) and is centered at $\alpha = 16^{\text{h}} 45^{\text{m}}$, $\delta = -12^{\circ} 00'$ (1950). It has an elongated filamentary structure which stretches over more than 4° mainly in the north-south direction. The thickness of the cloud varies somewhat over its length but is in general of the order of $10'$. At the southern end of the complex there is an extended cloud which is nearly perpendicular to the main filament. The distance to the L 204 complex has been estimated to ~ 170 pc and the mass to $\sim 400 M_{\odot}$ (McCutcheon et al., 1986). The most prominent part of the cloud complex, situated between $\delta = -10^{\circ} 45'$ and $= -13^{\circ} 10'$, consists of an almost continuous filament of nearly sinusoidal shape. Fig. 1a is a print from the Palomar Sky Atlas of this region. The wavelength and amplitude of the sine curve are $\sim 80'$ and $\sim 7'$, respectively.

Fig. 1b shows the same region in enhanced contrast where some of the filamentary features are better studied. It is evident from the pictures that the main filament is made up of at least two subfilaments. The division into subfilaments is most distinct in the declination ranges $\delta = -11^{\circ} 28'$ to $-11^{\circ} 52'$ and $\delta = -12^{\circ} 10'$ to $-12^{\circ} 20'$. Here, the subfilaments are fairly parallel to each other with a mutual separation of $\sim 5'$. It is possible that the subfilaments cross near the declinations $\delta = -11^{\circ} 20'$ and $\delta = -12^{\circ} 05'$, but this supposition is uncertain. A closer inspection of the Palomar prints shows a number of finer details. In Fig. 1c we have made a drawing of the cloud and the structures that we find. We want to underline that the contrast has been exaggerated in the figure in order to point out what features we believe are present. What is clearly present is the sinusoidal shape of the western subfilament in the interval $\delta = -11^{\circ} 28'$ to $-11^{\circ} 52'$ (feature A in Fig. 1c). This "wave" is on a much smaller scale than that seen in the main filament. About two complete waves are visible with a wavelength of $\sim 9'$ and an amplitude of $\sim 0.8'$.

Also the eastern subfilament (feature B) shows a remarkable shape. On the whole it resembles a twisted strip. Possibly, the eastern subfilament may consist of two still smaller filaments ("sub-subfilaments") winding around each other. The clearest indication of two sub-subfilaments is seen in the area around the position $\delta = -11^\circ 53'$ (feature C).

Another interesting part of the L 204 complex is the area with two or more weak arches (feature D) which bulge on the western side of the main filament from $\delta = -11^\circ 48'$ to $-11^\circ 58'$. The southern end of the arches seems to continue as thin filaments (feature E) across the main filament while bending further to the south. The impression is clearly that of two or more helices reaching $\sim 10'$ outside the western end of the main filament and kinking just outside the eastern edge.

As demonstrated by McCutcheon et al. (1986) the pattern of radial velocity of the cloud is very similar to the morphological structure of the cloud. According to these authors this suggests that the L 204 complex cannot be a sheet seen edge on - it is truly a filament. It is also to be noticed that the distribution of mass along the axis of the cloud seems to relate to the corresponding distribution of cloud motion.

From measurements of the Zeeman splitting of the 21 cm line of H, Heiles (1988) estimated the strength of the line-of-sight component of the magnetic field in the environment of the L 204 complex to about $12 \mu\text{G}$. The expected uncertainty is a factor of about two. Studies of the linear polarization of light from back-ground stars show that the E-vector is fairly perpendicular to the major axis of the cloud (McCutcheon et al., 1986). However, as stressed by Heiles (1987), there are a few deviations from this pattern near the center of the cloud where the E-vector is almost parallel to the major axis. On the assumption that the Davies-Greenstein mechanism applies, the E-vector should reflect a weighted mean direction of the magnetic field.

No sign-posts of star formation have been found in the main filament of the L 204 complex. For instance, there is no infrared source located within the cloud boundaries as inferred from the catalogue by Gezari et al. (1987). Hence, it is not likely that the motion of the cloud is disturbed by stars embedded in the clouds.

2.2 The Sandqvist 187-188 complex

This complex is centered at $\alpha = 16^{\text{h}} 30^{\text{m}}$, $\delta = -44^{\circ} 54'$. It is reproduced in Fig. 2a which is the picture which was taken and treated by H.-E. Schuster, G. Pizarro, and C. Madsen and described by Reipurth (1988). The cloud is very elongated and resembles a sword. The "hilt" of the sword (eastern part) is designated Sandqvist 187 (hereafter called Sa 187) while the "blade" is designated Sa 188 (see Sandqvist, 1977). The main part of the cloud is oriented mainly in the east-west direction. There is also an elongated cloud, "the cross-guard-bar", which is perpendicular to the main filament just as in the L 204 complex.

From tip to tip the Sa 187-188 complex spans about 40'. The distance to the cloud has been estimated to between 200 and 1300 pc (see e.g. Graham and Frogel, 1985). In view of the paucity of foreground stars seen on the deep ESO photographs we are inclined to think that the actual distance is closer to the lower limit of 200 pc. The morphology of Sa 187 is strikingly different from that of Sa 188. Here, we shall mainly concentrate on Sa 188. It is seen in Fig. 2a and indicated on the drawing in Fig. 2b that this cloud consists primarily of a main filament with a thickness of approximately 1' to 1.5'. The filament is not straight but forms a slightly wavy curve. In addition, there is evidence that the tip of the main filament forms a tightly wound helical structure (feature F in Fig. 2b). A closer inspection of the photograph reveals that there also appears to exist a much weaker filament of sinusoidal shape (feature G) which is superimposed on the main filament. Feature G is rather patchy and has a wavelength of $\sim 10'$ at the center of the cloud.

Also Sa 187 seems to consist of filaments (features H) which may form one or several loose helices. At present it is difficult to judge how these structures are related to one another.

Star formation has started in this complex. Sa 187 contains the Herbig-Haro objects HH 56 and 57 and the young star Reipurth 13 (see e.g. Alvarez et al., 1987). Sign-posts of star formation are also present in the blade at least at three locations (Reipurth, 1989).

3. The pinch model.

The special features appearing in the dust clouds discussed above are reminiscent of morphologies encountered in certain plasma experiments (see e.g. Peratt and Koert, 1983; Peratt, 1986). In particular we want to draw

the attention to the pinch phenomenon which has been a subject of study for many years in plasma physics, particularly in connection with fusion research. One of the simplest types of pinches is the Bennett pinch (see e.g. Spitzer, 1956) which consists of a cylindrical and fully ionized plasma carrying an axially directed current I_z . The current together with a consistent toroidal magnetic field gives rise to a pinching force directed inwards towards the axis of the cylinder. In the steady state this force is balanced by a pressure force of the plasma directed outwards. Denoting the number of electrons and ions (singly ionized) per unit length of the cylinder, $N_e = N_i$, and assuming the temperatures of the particles, T_e and T_i , to be constant Bennett (1934) could show that the relation

$$\mu_0 I_z^2 = 8\pi N_e k (T_e + T_i) \quad (3.1)$$

must be valid independently of how the current and the particles are distributed inside the cylinder.

In the dark filamentary clouds the physical conditions are certainly more complex than those assumed in the Bennett pinch. Hence, in order to describe the filamentary clouds we shall consider a more general type of pinch model which comprises a more complex current pattern and which beside electromagnetic forces and kinetic pressure forces also includes gravitational forces and centrifugal forces (Carlqvist, 1988). The model is constituted by a long current-carrying, cylindrical plasma of radius $r = a$. (Cylindrical coordinates r, ϕ, z are used with the z -axis coinciding with the axis of the plasma cylinder). The plasma consists of electrons, ions, and neutral gas with the densities n_e, n_i , and n_n and the temperatures T_e, T_i , and T_n , respectively. Furthermore the plasma carries a current of the density $\mathbf{i} = (0, i_\phi, i_z)$ consistent with the magnetic field $\mathbf{B} = (0, B_\phi, B_z)$. Hence, both the magnetic field and the current pattern are in general of helical shapes. The plasma in the cylinder may rotate about the z -axis with the angular velocity ω . It is assumed that all quantities vary with r only and that there is a close coupling between the charged particles and the gas. At the boundary of the cylinder the kinetic pressure is $p(a)$ while the axial component of the magnetic field is $B_z(a)$. Outside the cylinder the magnetic field is represented by a potential field.

In the equilibrium state the force equation of the plasma may be expressed as

$$\rho \, dv/dt = \mathbf{i} \times \mathbf{B} + \mathbf{F}_g - \text{grad } p_k . \quad (3.2)$$

Here $\rho = \bar{m}n$ is the mass density of the plasma where $\bar{m} = (m_e n_e + m_i n_i + m_n n_n)/n$ is the mean mass of the particles and $n = n_e + n_i + n_n$ is the total particle density. p_k is the total kinetic pressure of the particles. Since the motion of the plasma in the model consists of a pure rotation the inertia term in Equation (3.2) is given by

$$\rho \, dv/dt = - \rho \, \omega^2 r . \quad (3.3)$$

Furthermore the gravitational force at r is

$$F_g = -2G \bar{m}n / r^2 \cdot r \int_0^r 2\pi \bar{m}n \, dr \quad (3.4)$$

while the electromagnetic force may be written as

$$\mathbf{i} \times \mathbf{B} = \mathbf{i}_\phi \times \mathbf{B}_z + \mathbf{i}_z \times \mathbf{B}_\phi = -\text{grad } p_{Bz} + \mathbf{i}_z \times \mu_0 / 2\pi r \cdot \hat{\phi} \int_0^r 2\pi r \, i_z \, dr \quad (3.5)$$

where $p_{Bz} = B_z^2 / 2\mu_0$ is the magnetic pressure due to the axial component of the magnetic field. $\hat{\phi}$ is the unit vector in the ϕ -direction. It is to be noted that all forces have components in the radial direction only. Introducing the axial current inside r

$$I_z(r) = \int_0^r 2\pi r \, i_z \, dr \quad (3.6)$$

and the linear density (particles per unit length) inside r

$$N(r) = \int_0^r 2\pi r \, n \, dr \quad (3.7)$$

we may integrate Equation (3.2) from the axis out to radius $r = a$ (see Carlqvist, 1988) and find

$$\mu_0 I_z^2(a) + 4\pi G \bar{m}^2 N^2(a) = 8\pi [\Delta W_k(a) + \Delta W_{Bz}(a) + \Delta W_{rot}(a)] \quad (3.8)$$

where

$$\Delta W_k(a) = \int_0^a 2\pi r p_k dr - \pi a^2 p_k(a) \quad (3.9)$$

$$\Delta W_{Bz}(a) = \int_0^a 2\pi r p_{Bz} dr - \pi a^2 p_{Bz}(a) \quad (3.10)$$

$$\Delta W_{rot}(a) = \int_0^a (2\pi r \bar{m} n \omega^2 r^2 / 2) dr. \quad (3.11)$$

Equation (3.8) expresses the condition for equilibrium of the current-carrying, self-gravitating and rotating plasma cylinder. The relation between the current $I_z(a)$ and the linear density $N(a)$ is shown in Fig. 3 for some discrete values of $\Delta W_{Bz} = \Delta W_{Bz}(a)$ in the case of a non-rotating plasma ($\omega = 0$) with $p_k(a) \ll p_k(0)$, $T = 20$ K, and $\bar{m} = 4 \cdot 10^{-27}$ kg (representing 80% H_2 and 20% He). An equilibrium condition similar to Equation (3.8) may be obtained also for a plasma slab of plane geometry (Carlqvist, 1988).

4. Discussion.

4.1 Magnetic fields and electric currents.

In both the L 204 complex and the Sa 187-188 complex dark material is collected into very elongated filamentary structures. This fact by itself suggests that a very efficient mechanism for pinching is operative in both of the clouds. In principle there are several forces which may give rise to pinching of the cloud matter such as the force of gravity, the electromagnetic force, and an external pressure force. However, in our opinion only the

electromagnetic force is capable of producing all the characteristic structures seen in the clouds.

Examples of such characteristic structures in the Sa 187-188 complex are the spiral appearance of the main filament (feature F in Fig. 2b), the filamentary nature of the hilt of the sword (features H) and the apparent sinusoidal shape of the subfilament (feature G). The three-dimensional geometry of the subfilament may be either a helix or a plane sine curve. Both of these geometries are indicative of electric currents and magnetic fields (see Section 4.3).

It is interesting to notice that on the whole the Sa 187-188 complex has several morphological features in common with ascending solar prominences which are known to carry considerable electric currents and to be dominated by electromagnetic forces.

In the L 204 complex there are also several structures for which similar conclusions can be drawn. First of all, the L 204 complex appears to consist of two or more subfilaments which possibly are wound around each other like threads in a wire. Furthermore, the western subfilament (feature A, Fig. 1c) may in three dimensions represent a helix or a plane sine curve while the eastern subfilament seems to consist of at least two sub-subfilaments (features B and C). All these structures are difficult to explain without reference to dominant electromagnetic forces.

The perhaps clearest evidence of a helical structure is found in features D and E. Assuming the structure to be aligned with the magnetic field we can estimate the axial current in the main filament from the tilt of the features and the strength of the magnetic field B . With $B = 1 \cdot 10^{-9} - 2 \cdot 10^{-9} \text{ T} = 10 - 20 \text{ } \mu\text{G}$ we find an axial current in the main filament of $I_z \approx 10^{13} - 10^{14} \text{ A}$.

4.2 *Pinching of the clouds.*

Already many years ago it was suggested that the dense interstellar clouds are subject to pinching due to electric currents (Bruce, 1963; Alfvén and Carlqvist, 1978). In order to find out the magnitude of the currents required for such a pinching we shall apply the generalized pinch equation (3.8) to a few filaments in the L 204 complex. In particular we shall study the western subfilament (feature A) in the declination range $-11^\circ 50'$ to $-11^\circ 30'$. We assume that the temperature of the cloud is $T = 20 \text{ K}$, $\bar{m} = 4 \cdot 10^{-27} \text{ kg}$, $p_k(0) \gg p_k(a)$, and $\omega = 0$.

As given by McCutcheon et al. (1986) the total mass of the complex in the interval considered is $\sim 24 M_{\odot}$. We estimate that $\sim 2/3$ of this mass is present in the western subfilament. With a distance to L 204 of 170 pc the projected length of the subfilament in the declination interval is $3.2 \cdot 10^{16}$ m. Since we do not know the angle between the line-of-sight and the axis of the subfilament we cannot with certainty determine the real length of the subfilament. Instead we shall as a measure of the real length use the most probable length, l_p , which is obtained by multiplying the projected length by $4/\pi$. Hence, we obtain the linear density of the particles in the subfilament $N = 24 M_{\odot} / \bar{m} l_p = 2 \cdot 10^{41} \text{ m}^{-1}$. If we first suppose that $B_z = 0$, implying that $\Delta W_{Bz} = 0$, we find from Equation (3.8) or Fig. 3 that the axial current necessary for equilibrium is $I_z = 2.6 \cdot 10^{13} \text{ A}$.

The helical structure indicated by features D and E, shows that there may exist an axial component of the magnetic field in the cloud. Choosing $B_z = 10^{-9} \text{ T} = 10 \mu\text{G}$ and using the radius of the subfilament, $a = 3.3 \cdot 10^{15} \text{ m}$, we obtain $\Delta W_{Bz} = \pi a^2 B_z^2 / (2\mu_0) = 1.4 \cdot 10^{19} \text{ J m}^{-1}$. From Equation (3.8) or Fig. 3 we now find an axial current of $I_z = 3.1 \cdot 10^{13} \text{ A}$.

With an axial current of $3 \cdot 10^{13} \text{ A}$ the azimuthal component of the magnetic field in the outer parts of the subfilament is $B_{\phi}(a) = 1.8 \cdot 10^{-9} \text{ T} = 18 \mu\text{G}$. This current corresponds to a mean current density of $i_z = I_z / \pi a^2 \approx 10^{-18} \text{ A m}^{-2}$. Using a degree of ionization of $n_e/n_n \approx 10^{-7} - 10^{-4}$, which is sometimes discussed in connection with molecular clouds (see e.g. Hjalmarsson and Friberg, 1988; Black and van Dishoeck, 1991), we find the mean drift velocity of the electrons to be $v_{ez} \approx i_z / en_e \approx 10^{-5} - 10^{-2} \text{ m s}^{-1}$. Because of inhomogeneities it can be expected that the maximum values of both the current density and the electron drift velocity will be larger than the values given above.

In the same way as we have estimated the axial current in the western subfilament we may also estimate the current in the eastern subfilament. The result is $I_z \approx 3 \cdot 10^{13} \text{ A}$. Hence, if the currents in both of the subfilaments flow in the same direction the total axial current in the L 204 complex should be of the order of $I_z \approx 6 \cdot 10^{13} \text{ A}$ in agreement with the results obtained in Section 4.1.

In case of a rotating filament ($\omega \neq 0$) the centrifugal force will be of significant importance for the force balance in the subfilament only if the typical velocity of rotation $v_{\text{rot}} \geq 5 \cdot 10^2 \text{ m s}^{-1}$.

4.3 *Instabilities.*

The peculiar velocity pattern of the L 204 complex found by McCutcheon et al. (1986) deserves a closer examination. McCutcheon et al. considered the possibility that the specific motion of the cloud complex might result through the interaction with a strong stellar wind from the run-away star ζ Oph. Here we want to point at another possibility based on the kink instability.

From both theoretical investigations and laboratory experiments it is well known that pinches, under certain conditions, suffer from various kinds of instabilities (see e.g. Alfvén and Fälthammar, 1963). The Bennett pinch, for instance, always seems to be unstable. One important mode of instability is the kink instability which originates from a disturbance that takes the form of a small kink or sine wave of the pinched filament. The disturbance gives rise to non-symmetric electromagnetic forces which are larger on the concave side of the filament than on the convex side. Owing to this asymmetry the deformation is amplified leading to an unstable situation.

In essentially the same way as the kink instability occurs in laboratory pinches it may also occur in pinched dark clouds like the L 204 complex. As a result of the instability the cloud may be deformed into a pronounced sinusoidal shape (or S-shape). Furthermore, if the kink grows in a plane which is not perpendicular to the line of sight, we should expect a radial velocity pattern in accordance with what is observed for the L 204 complex.

Another type of instability that may develop in pinches is the sausage instability. It arises from a small radial disturbance of the pinched filament (e.g. one or several constrictions) and may lead to disruption of the filament. Also this kind of instability can under certain conditions (Alfvén and Fälthammar, 1963) be expected to occur in pinched dark clouds where it may cause fragmentation of the clouds.

In the pinch model discussed in Section 3 we have limited ourselves to a pure cylindrical geometry. However, in cosmic plasmas the geometry is likely to be more complex. For instance, it is possible that the main filament, as a result of either an initially inhomogeneous current distribution or an instability of the tearing mode type, may be split up into a number of subfilaments. This is what we believe could have happened in the L 204 and Sa 187-188 complexes. It is expected that the large scale pattern of the individual subfilaments should be helical just as the magnetic field pattern

in the cylindrical pinch is helical. An analogue of this phenomenon is often seen in ascending prominences.

In general we anticipate that instabilities of various kinds should initiate a whole spectrum of Alfvén waves. Hence, such waves should quite naturally be present in pinched dark clouds.

Above we have drawn the attention to filamentary structures of helical shape in the L 204 complex and in the Sa 187-188 complex. It is interesting to note that Uchida et al. (1991) have recently observed a similar helical structure in the L 1641 molecular cloud in the Orion complex. As in the case of L 204 the pattern of radial velocity of L 1641 resembles the morphological structure of the cloud.

Finally, it should be pointed out that Woltjer (1958) considered the bright filaments in the Crab nebula and developed a theory in which they represent concentrated electric currents.

4.4 Future investigations.

The present investigation has shown that the complicated structures seen in two molecular clouds can be understood in terms of electromagnetic forces. We have also demonstrated that the mean current densities implied are small enough for the mean drift velocity of the electrons to be much smaller than the thermal velocities in the clouds. Therefore, if the cloud filaments are not very inhomogeneous, the currents can be carried without any other dramatic effects resulting on the clouds than the pinching discussed above.

The two cloud complexes investigated are not the only ones with filamentary structures of the kind reported here. It could therefore be of interest to make a similar analysis of other clouds to see what the range of the inferred parameters is.

With regard to the L 204 and Sa 187-188 complexes there are several observational tests that can be made to check the validity of the proposed model. Firstly, detailed mapping of the filaments and subfilaments should be made in for instance ^{13}CO , especially at points where the filaments seem to cross each other. If the subfilaments are helices wound around the main filament, then they could be separated in velocity and also each filament will appear as a continuous entity in the distribution of mass and velocity.

It is furthermore of great interest to obtain mappings of the Zeeman splitting of lines at higher spatial resolution. In addition, polarization measurements of back-ground stars are of interest. As mentioned in Section

2, stars located deeply behind the clouds do indicate E-vectors more parallel to the cloud axis. However, the present sample of such stars is very small. Additional polarization measurements may provide a more detailed picture of both the magnetic fields and the electric currents in the dark molecular clouds.

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Figure 1. a (left) shows a photocopy from the Palomar Sky Atlas of the central main filament in the L 204 complex. b (middle) shows the same area but on a high contrast photocopy. c (right) is a drawing of the region where certain structures discussed in the text are labeled.

Figure 2. a (above) shows the negative of a photograph of the cloud complex Sandqvist 187-188 produced by C.Madsen, G. Pizarro, B. Reipurth, and H.-E. Schuster [12]. b (below) is a drawing of the same complex where certain structures discussed in the text are labeled.

Figure 3. The axial current of the pinch, I_z , is shown as a function of the linear density, N , for a few different values of ΔW_{Bz} (given in units of J m^{-1}). It is assumed that $\omega = 0$, $p_k(0) \gg p_k(a)$, $\bar{m} = 4 \cdot 10^{-27} \text{ kg}$, and $T = 20 \text{ K}$. The pinch illustrated is governed by electromagnetic forces, kinetic pressure forces, and gravitational forces being in equilibrium with one another. The straight part of the curve labeled $\Delta W_{Bz} = 0$ represents the Bennett relation. For larger values of ΔW_{Bz} in the upper left-hand part of the diagram the magnetic field of the pinch tends towards a more force-free geometry. The vertical parts of the curves to the right illustrate a situation where the gravitational force is balanced mainly by a magnetic pressure force due to the B_z component.

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MANIFESTATIONS OF ELECTRIC CURRENTS IN INTERSTELLAR MOLECULAR CLOUDS

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Abstract

We draw the attention to filamentary structures in molecular clouds and point out the existence of subfilaments of sinusoidal shape and also of helix-like structures. For two dark clouds, the Lynds 204 complex and the Sandqvist 187-188 complex (The Norma "sword") we make a detailed study of such shapes and in addition we find the possible existence of helices wound around the main filaments. All these features are highly reminiscent of morphologies encountered in solar ascending prominences and in experiments in plasma physics and suggest the existence of electric currents and magnetic fields in these clouds.

On the basis of a generalization of the Bennett pinch model, we derive the magnitudes of the currents expected to flow in the filaments. Values of column densities, magnetic field strengths, and direction of the fields are derived from observations. Magnetic fields with both toroidal and axial components are considered. This study shows that axial currents of the order of a few times 10^{13} A are necessary for the clouds to be in equilibrium. The corresponding mean current densities are very small and even at the very low values of the fractional abundance of electrons encountered in these clouds, the mean electron velocities are of the order of 10^{-2} - 10^{-5} m s⁻¹, much lower than the thermal velocities in the clouds.

We suggest that helical structures may evolve as a result of various instabilities in the pinched clouds. We also call the attention to the kink instability in connection with the sinusoidal shapes. The existence of electromagnetically controlled features in the interstellar clouds can be tested by further observations.

Key words: Molecular clouds, Electric Currents, Magnetic fields, Pinch, Lynds 204, Sandqvist 187-188