Mon. Not. R. Astron. Soc. **330,** 901–906 (2002)

# Helicoidal magneto-electron waves in interstellar molecular clouds

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Accepted 2001 November 6. Received 2001 September 14; in original form 2001 April 24

## ABSTRACT

We investigate the evolution of the magnetic flux density in a magnetically supported molecular cloud driven by Hall and Ohmic components of the electric field generated by the flows of thermal electrons. Particular attention is given to the wave transport of the magnetic field in a cloud whose gas dynamics is dominated by electron flows; the mobility of neutrals and ions is regarded as heavily suppressed. It is shown that electromagnetic waves penetrating such a cloud can be converted into helicons – weakly damped, circularly polarized waves in which the densities of the magnetic flux and the electron current undergo coherent oscillations. These waves are interesting in their own right, because for electron magnetohydrodynamics the low-frequency helicoidal waves have the same physical significance as the transverse Alfvén waves do for a single-component magnetohydrodynamics. The latter, as is known, are considered to be responsible for the widths of molecular lines detected in dark, magnetically supported clouds. From our numerical estimates for the group velocity and the rate of dissipation of helicons it follows that a possible contribution of these waves to the broadening of molecular lines is consistent with the conditions typical of dark molecular clouds.

**Key words:** MHD – polarization – waves – ISM: clouds – ISM: magnetic fields.

## 1 INTRODUCTION

The gas-dynamical processes in star-forming molecular clouds are primarily determined by the strong coupling of a gas–dust interstellar medium (ISM) with magnetic fields. As electrons are one of the most abundant and mobile charged components of ISM, and their small mass provides the strongest coupling with intercloud magnetic fields, it is natural to expect that the collective behaviour of electrons may essentially affect the interstellar gas dynamics.

The well known example of the collective behaviour of electrons in the presence of a uniform magnetic field is the high-frequency cyclotron wave. However, the propagation of these waves in the interstellar medium is heavily suppressed. This conclusion can easily be drawn from the hydrodynamical model of a viscous electron fluid, whose motions in a permanent magnetic field, $\boldsymbol{B} = \text{constant}$, are controlled by the Lorentz force:

$$\frac{\mathrm{d}\rho_{\mathrm{e}}(\boldsymbol{r},t)}{\mathrm{d}t} + \rho_{\mathrm{e}}(\boldsymbol{r},t)\nabla\cdot\boldsymbol{u}(\boldsymbol{r},t) = 0,$$

$$\mathrm{d}/\mathrm{d}t = \partial/\partial t + \boldsymbol{u}(\boldsymbol{r},t)\cdot\nabla, \tag{1}$$

$$\rho_{\mathrm{e}}\frac{\mathrm{d}\boldsymbol{u}(\boldsymbol{r},t)}{\mathrm{d}t} = \frac{en_{\mathrm{e}}}{c}[\boldsymbol{u}(\boldsymbol{r},t)\times\boldsymbol{B}] + \eta\nabla^2\boldsymbol{u}(\boldsymbol{r},t),$$

$$\rho_{\mathrm{e}}(\boldsymbol{r},t) = m_{\mathrm{e}}n_{\mathrm{e}}(\boldsymbol{r},t). \tag{2}$$

Hereafter $m_e$ is the mass of electron, $n_e(\boldsymbol{r}, t)$ is the electron density, $\boldsymbol{u}(\boldsymbol{r},t)$ is the directed velocity of electron flow, and $\eta$ stands for the dynamical viscosity of electron fluid that effectively accounts for all dissipative effects of elastic collisions of electrons with other microparticles of the cloud, basically neutrals. By considering electrons as an incompressible fluid, $\rho_{\mathrm{e}} = \text{constant}$, we linearize the above equations about a homogeneous undisturbed state with $\boldsymbol{u} = 0$. Making use of the standard procedure of linearization, $\boldsymbol{u}(\boldsymbol{r},t) \to \boldsymbol{u} + \delta\boldsymbol{u}(\boldsymbol{r},t)$, we obtain[1]

$$\nabla\cdot\delta\boldsymbol{u}(\boldsymbol{r},t) = 0,$$

$$\frac{\partial\,\delta\boldsymbol{u}(\boldsymbol{r},t)}{\partial t} = \frac{e}{m_{\mathrm{e}}c}[\delta\boldsymbol{u}(\boldsymbol{r},t)\times\boldsymbol{B}] + \frac{\eta}{\rho_{\mathrm{e}}}\nabla^2\,\delta\boldsymbol{u}(\boldsymbol{r},t). \tag{3}$$

[1] It is worth noting that cyclotron waves can be regarded as an analogue of inertial waves in a rotating incompressible fluid governed by equations (Chandrasekhar 1961)

$$\nabla\cdot\delta\boldsymbol{u}(\boldsymbol{r},t) = 0, \quad \frac{\partial\,\delta\boldsymbol{u}(\boldsymbol{r},t)}{\partial t} = 2[\delta\boldsymbol{u}(\boldsymbol{r},t)\times\boldsymbol{\Omega}] + \nu\nabla^2\,\delta\boldsymbol{u}(\boldsymbol{r},t),$$

where $\nu = \eta/\rho$ is the kinematic viscosity.

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Making use of the plane-wave form for $\delta\boldsymbol{u}(\boldsymbol{r},t) \propto \exp \mathrm{i}(\boldsymbol{k}\cdot r - \omega t)$ in the right-hand side of equations (3), one has $\boldsymbol{k}\cdot\delta\boldsymbol{u} = 0$, which implies that the wave is transverse. Inserting the plane-wave form of $\delta\boldsymbol{u}$ into an equation of motion, the left-hand side of equations (3), we obtain the dispersion relationship

$$\omega = \pm\omega_{\mathrm{c}}(1 \pm i\Gamma_{\mathrm{c}}), \quad \omega_{\mathrm{c}} = \frac{eB}{m_{\mathrm{e}}c}, \quad \Gamma_{\mathrm{c}} = \frac{\eta k^2}{\omega_{\mathrm{c}}\rho_{\mathrm{e}}}. \tag{4}$$

From the above it follows that interstellar cyclotron waves are transverse, circularly polarized and damped. Their group velocity is given by

$$\boldsymbol{V}_{\mathrm{c}} = \frac{\partial\omega}{\partial\boldsymbol{k}} = \pm\frac{e}{m_{\mathrm{e}}c}\frac{\boldsymbol{k}\times[\boldsymbol{B}\times\boldsymbol{k}]}{k^3}. \tag{5}$$

The two last equations are identical to those for the dispersion relation and group velocity of the inertial wave propagating in a homogeneously rotating incompressible liquid, which are due to Chandrasekhar (5). The interested reader can find a detailed derivation of the above equations in the latter monograph. To get an idea about the effect of cyclotron waves on gas dynamics of magnetically supported clouds we consider the case $\boldsymbol{k} \perp \boldsymbol{B}$. In this case the group velocity is given by

$$V_{\mathrm{c}} = \frac{\omega_{\mathrm{c}}}{k}. \tag{6}$$

Typically, the mean electron density is $10^{-3}\,\mathrm{cm}^{-3}$, the average intensity of magnetic field is $10^{-5}$ Gauss and the average electron temperature is 10–200 K. By putting $V_{\mathrm{c}} \approx 0.3$–$0.5\,\mathrm{km\,s}^{-1}$ (the realm of the observed molecular linewidths) we can estimate the wavelength of the cyclotron wave: $\lambda_{\mathrm{c}} \approx 10^2$–$10^3$ cm. The coefficient of viscosity in the interstellar electron fluid can be evaluated as follows (Golant, Zhilinski & Zakharov 1980): $\eta \approx n_{\mathrm{e}}k_BT_{\mathrm{e}}/\nu_{\mathrm{c}}$ g/(cm s). The frequency of elastic collisions of electrons with ions and neutrals is typically in the interval $\nu_{\mathrm{c}} \approx 10^{-3}$–$10^{-1}\,\mathrm{s}^{-1}$ (Mouschovias 1987). Under the above parameters, the magnitude of the damping coefficient $\Gamma_{\mathrm{c}} \approx 10^3$–$10^4$. This is in strong conflict with the criterion of propagation of the cyclotron wave, $\Gamma_{\mathrm{c}} \ll 1$, found from equation (4). Therefore, the cyclotron waves in dark interstellar clouds must be highly damped.

In this paper we discuss a different model of magneto-electron wave motions in a uniformly magnetized interstellar cloud which are not directly connected with inertial motions of electrons. The wave process under consideration is associated with the transport of the magnetic flux density driven by the Hall component of the electric field induced by the flows of the thermal electrons. To accentuate the physical features of these waves, we confine our consideration to a purely electron gas dynamics by ignoring the mobility of ions and neutral molecules. The presence of these latter components in the cloud is taken into account by the effects of elastic collisions of electrons with ions and neutrals, resulting in an Ohmic decay of the magnetic field. Understandably, the approximation of the immobility of ions and neutrals eliminating the ambipolar diffusion might be a matter of controversy. Nevertheless, it does not affect the interest in the problem as such. To the best of our knowledge, the problem of magneto-electron waves has not been touched upon in the literature, whereas for electron magneto-hydrodynamics these waves have the same physical significance as Alfvén waves for the gas dynamics of interstellar magnetoplasma.

It should be mentioned that the magneto-electron waves under consideration were first discovered in the physics of solid-state plasmas. The name helicons was coined (Konstantinov & Perel 1960; Kaner & Skobov 1966; Platzmann & Wolff 1970) as a result the spiral character of these circularly polarized waves. The helicons represent a low-frequency branch of electromagnetic excitation in a non-compensated electron-dominated magneto-plasma; the frequency of electron oscillations in this wave is less than the cyclotron frequency (e.g. Akhiezer et al. 1975). Waves of a similar nature are observed in planetary magnetospheres. In particular, the propagation of helicons in the Earth's ionosphere causes the whistling audio noise on a radio; for this reason these waves are often called whistlers (Akhiezar et al. 1975; Parks 1991). The analogous Hall mechanism of the wave transport of a magnetic flux density by electrons has recently been discussed by Goldreich & Reisenegger (1992) and Thompson & Duncan (1996) in the context of the magnetic field evolution in the radio pulsars and magnetars.

The organization of this paper is set out as follows. In Section 2, the governing equations for the transport of a magnetic flux density by the Hall and Ohmic components of the electric field, generated by flows of thermal electrons, are introduced. In Section 3 we derive the dispersion relation for helicons and evaluate the group velocity for their propagation in the interstellar medium, with parameters inferred from the pulsar dispersion measure of Galactic disc. The application of the model to the dark molecular clouds is considered in Section 3. In Section 4 a brief outlook is given for the model considered here in juxtaposition with other models of wave gas-dynamical processes in dark interstellar clouds which could affect the broadening of the molecular lines.

## 2 GOVERNING EQUATIONS

As was mentioned earlier, the cyclotron waves characterize a high-frequency branch of collective oscillatory behaviour of electrons in interstellar magnetoplasma. The model under consideration focuses on the low-frequency magneto-electron waves which originate from the transport of the magnetic flux density by thermal electrons, due to Hall electron conductivity.

In what follows we confine our consideration to an idealized model of the isothermal intercloud medium whose gas dynamics is dominated by thermal electrons. The magnetic field is considered to be frozen into the ions, whose mobility, together with that of the neutral molecules, is assumed to be heavily suppressed, so these latter are regarded as immobilized. This suggests that the collective behaviour of intercloud electrons in the presence of permanent magnetic field should have some features in common with that for conductive electrons in a metal solid, where the immobility of the ions is taken for granted. Following this line of argument, we take advantage of the constitutive equation for the electron conductivity in the form of a generalized Ohm's law;

$$\boldsymbol{E}(\boldsymbol{r},t) = \frac{\boldsymbol{j}(\boldsymbol{r},t)}{\sigma_{\mathrm{c}}} + \frac{1}{ecn_{\mathrm{e}}}\left[\boldsymbol{B}(\boldsymbol{r},t)\times\boldsymbol{j}(\boldsymbol{r},t)\right] = \frac{\boldsymbol{j}}{\sigma_{\mathrm{c}}} + \frac{[\boldsymbol{n}_B\times\boldsymbol{j}]}{\sigma_{\mathrm{H}}},$$

$$\boldsymbol{n}_B = \frac{\boldsymbol{B}}{B}, \tag{7}$$

$$\sigma_{\mathrm{c}} = \frac{n_{\mathrm{e}}e^2}{m_{\mathrm{e}}\nu_{\mathrm{c}}}, \quad \sigma_{\mathrm{H}} = \frac{en_{\mathrm{e}}c}{B},$$

$$\boldsymbol{j}(\boldsymbol{r},t) = \frac{c}{4\pi}\nabla\times\boldsymbol{B}(\boldsymbol{r},t). \tag{8}$$

Here the Ohmic conductivity $\sigma_{\mathrm{c}}$ is given by Drude formula, $\sigma_{\mathrm{H}}$ stands for the Hall conductivity and $\boldsymbol{j}(\boldsymbol{r},t)$ is the density of electron current, in accord with Ampére law. Taking into account that the magnetic flux density obeys Maxwell's equation for Faraday induction,

$$\frac{\partial \boldsymbol{B}(\boldsymbol{r},t)}{\partial t} = -c\nabla\times\boldsymbol{E}(\boldsymbol{r},t), \tag{9}$$

and inserting (7) and (8) into (9), we obtain

$$\frac{\partial \boldsymbol{B}(\boldsymbol{r},t)}{\partial t} = -\frac{c}{4\pi e n_{\mathrm{e}}}\nabla\times\{\boldsymbol{B}(\boldsymbol{r},t)\times[\nabla\times\boldsymbol{B}(\boldsymbol{r},t)]\} + \frac{c^2}{4\pi\sigma_{\mathrm{c}}}\nabla^2\boldsymbol{B}(\boldsymbol{r},t). \tag{10}$$

It is worth noting that the model under consideration can be considered as an idealized version of that constructed by Mouschovias (1987) in the context of redistribution of the magnetic flux in cores of interstellar magnetically supported clouds with ions that are frozen into the magnetic field threading the cloud. The first term on the right-hand side of equation (10) is due to Hall electron conductivity and the second term describes Ohmic diffusion of magnetic field. Understandably, the diffusion-free regime of the magnetic flux transport is realized when $\sigma_{\mathrm{c}} \gg \sigma_{\mathrm{H}}$. In this regime the equation (10), supplemented by the condition of solenoidality for $\boldsymbol{B}(\boldsymbol{r}, t)$, takes the form

$$\frac{\partial \boldsymbol{B}(\boldsymbol{r},t)}{\partial t} = -\frac{c}{4\pi e n_{\mathrm{e}}}\nabla\times\{\boldsymbol{B}(\boldsymbol{r},t)\times[\nabla\times\boldsymbol{B}(\boldsymbol{r},t)],$$
$$\nabla\cdot\boldsymbol{B}(\boldsymbol{r},t) = 0, \tag{11}$$

from which it follows that the total magnetic energy in the cloud volume,

$$W_m = \frac{1}{8\pi}\int \boldsymbol{B}^2\,\mathrm{d}V, \tag{12}$$

is conserved:

$$\frac{\mathrm{d}W_m}{\mathrm{d}t} = \frac{1}{4\pi}\int \boldsymbol{B}\cdot\frac{\partial\boldsymbol{B}}{\partial t}\mathrm{d}V = \frac{c}{16\pi^2 e n_{\mathrm{e}}}\int[(\nabla\times\boldsymbol{B})\times\boldsymbol{B}]\cdot(\nabla\times\boldsymbol{B})\,\mathrm{d}V = 0. \tag{13}$$

It is the major purpose of the remainder of this paper to show that interstellar magnetoplasma of molecular star-forming clouds can transmit low-frequency perturbations in the magnetic flux density by weakly damped helicoidal circularly polarized waves, which owe their existence to the Hall drift of the magnetic field by flows of thermal electrons.

## 3 HELICOIDAL MAGNETO-ELECTRON WAVES

Let us consider evolution of small-amplitude perturbations in magnetic flux density $\delta\boldsymbol{B}$, superimposed on the permanent magnetic field $\boldsymbol{B}$

$$\boldsymbol{B}(\boldsymbol{r},t)\rightarrow\boldsymbol{B}+\delta\boldsymbol{B}(\boldsymbol{r},t), \quad \boldsymbol{B}=\text{constant}. \tag{14}$$

The linearization of equation (10) with the aid of the substitution of (14) leads to

$$\frac{\partial\,\delta\boldsymbol{B}}{\partial t} = \frac{c}{4\pi n_{\mathrm{e}} e}(\boldsymbol{B}\cdot\nabla)[\nabla\times\delta\boldsymbol{B}] + \frac{c^2}{4\pi\sigma_{\mathrm{c}}}\nabla^2\delta\boldsymbol{B}, \nabla\cdot\delta\boldsymbol{B} = 0. \tag{15}$$

By substituting

$$\delta\boldsymbol{B} = \boldsymbol{b}\exp[\mathrm{i}(\boldsymbol{k}\cdot r - \omega t)] \tag{16}$$

into equations (15), we obtain

$$\frac{\partial\,\delta\boldsymbol{B}}{\partial t} = -\frac{c^2}{4\pi\sigma_{\mathrm{H}}}(\boldsymbol{k}\cdot\boldsymbol{n}_B)(\boldsymbol{k}\times\delta\boldsymbol{B}) + \frac{c^2}{4\pi\sigma_{\mathrm{c}}}[\boldsymbol{k}\times(\boldsymbol{k}\times\delta\boldsymbol{B})],$$
$$\boldsymbol{k}\cdot\delta\boldsymbol{B} = 0. \tag{17}$$

Let the permanent field $\boldsymbol{B}$ be directed along $z$-axis: $\boldsymbol{B} = [0, 0, B]$, and consider a one-dimensional plane-wave perturbation along the $z$-axis ($\boldsymbol{k} = k\mathbf{e}_z$) that does not affect the intensity of the magnetic field in this direction, but only along the $x$- and $y$-directions. This means that components of the fluctuating magnetic field depend only upon $z$ and $t$:

$$\delta B_x(z,t) = b_x\exp\mathrm{i}(kz-\omega t),$$
$$\delta B_y(z,t) = b_y\exp\mathrm{i}(kz-\omega t),$$
$$\delta B_z = 0. \tag{18}$$

The Cartesian components of equation (17) can be represented as follows:

$$\frac{\partial\,\delta B_x}{\partial t} = +\frac{c^2k^2}{4\pi\sigma_{\mathrm{H}}}\delta B_y - \frac{c^2k^2}{4\pi\sigma_{\mathrm{c}}}\delta B_x, \tag{19}$$

$$\frac{\partial\,\delta B_y}{\partial t} = -\frac{c^2k^2}{4\pi\sigma_{\mathrm{H}}}\delta B_x - \frac{c^2k^2}{4\pi\sigma_{\mathrm{c}}}\delta B_y. \tag{20}$$

To see that the wave motions in question bear a circularly polarized character, we omit for the moment the term of Ohmic diffusion. Then, the resultant equations (19) and (20) become $\delta B_x = -\Omega_z\delta B_y$ and $\delta B_y = \Omega_z\delta B_x$. These two equations are the Cartesian components of the vector equation $\delta\dot{\boldsymbol{B}} = (\boldsymbol{\Omega}\times\delta\boldsymbol{B})$, which describe the precession of the vector $\delta\boldsymbol{B}$ about the $z$-axis with the angular frequency $\boldsymbol{\Omega} = -[(cB)/(4\pi n_{\mathrm{e}}e)]\mathrm{k}^2\mathbf{e}_z$.

The kinematic character of these wave motions is illustrated in Fig. 1. As is known, this sort of wave motion is customarily described in terms of the right-hand $\delta B_+$ and the left-hand $\delta B_-$ circularly polarized waves;

$$\delta B_+ = \delta B_x + i\delta B_y = b(z)\exp(-\mathrm{i}\omega t),$$
$$\delta B_- = \delta B_x - i\delta B_y = b(z)\exp(\mathrm{i}\omega t). \tag{21}$$

Combining the coupled equations (19) and (20) to obtain one equation for $\delta B_+$, we arrive at

$$\frac{\partial\,\delta B_+}{\partial t} = -i\frac{c^2k^2}{4\pi\sigma_{\mathrm{H}}}\delta B_+ - \frac{c^2k^2}{4\pi\sigma_{\mathrm{c}}}\delta B_+. \tag{22}$$

By eliminating the time derivative with the help of (21), we obtain

$$\omega = \omega_{\mathrm{h}}(1-i\Gamma_{\mathrm{h}}), \omega_{\mathrm{h}} = \frac{c^2k^2}{4\pi\sigma_{\mathrm{H}}} = \frac{\omega_{\mathrm{c}}}{\omega_{\mathrm{p}}^2}c^2k^2, \Gamma_{\mathrm{h}} = \frac{\sigma_{\mathrm{H}}}{\sigma_{\mathrm{c}}} = \frac{\nu_{\mathrm{c}}}{\omega_{\mathrm{c}}}, \tag{23}$$

where

$$\omega_{\mathrm{c}} = \frac{eB}{m_{\mathrm{e}}c}, \omega_{\mathrm{p}}^2 = \frac{4\pi e^2 n_{\mathrm{e}}}{m_{\mathrm{e}}}.$$

Similarly, for $\delta B_-$ we obtain

$$\frac{\partial\,\delta B_-}{\partial t} = i\frac{c^2k^2}{4\pi\sigma_{\mathrm{H}}}\delta B_- - \frac{c^2k^2}{4\pi\sigma_{\mathrm{c}}}\delta B_-, \tag{24}$$

which, after the substitution of (21), leads to $\omega = \omega_{\mathrm{h}}(1+i\Gamma_{\mathrm{h}})$. In electron magnetohydrodynamics (Kingsep, Chukbar & Yan'kov 1990), the helicons play the same role as the transverse Alfvén waves do in the single-component magnetohydrodynamics (MHD) (Chandrasekhar 1961). In both kinds of these MHD waves, the

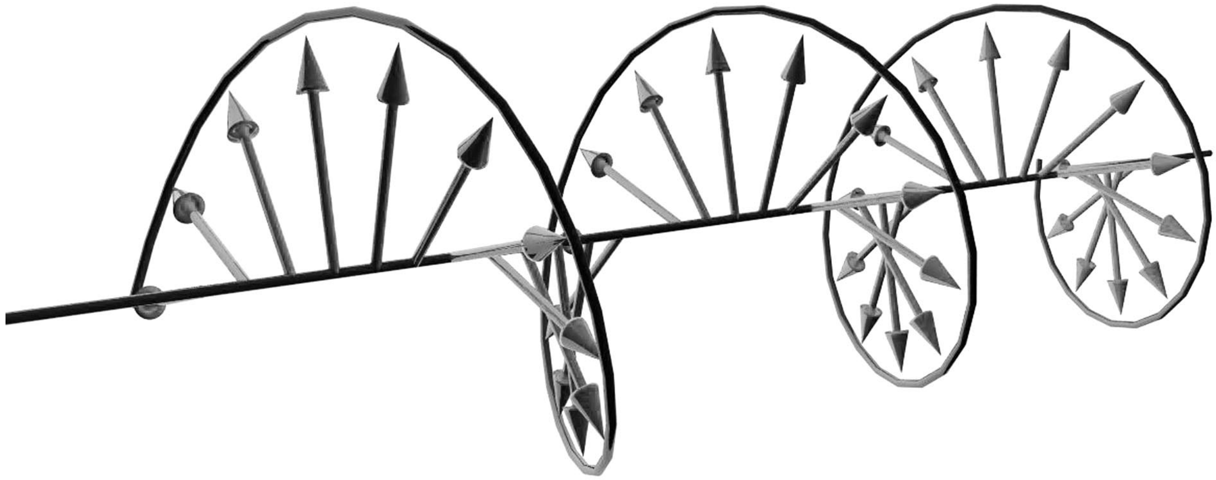

**Figure 1.** Schematic picture for oscillations of the magnetic field vector in the helicoidal magneto-electron wave.

oscillatory motions of conducting fluid are strongly coupled with fluctuations of magnetic field. The essential kinematic difference between them is that the group velocity of a helicoidal magneto-electron wave depends on frequency, whereas Alfvén waves are characterized by dispersion-free law of propagation: $\omega = V_{\rm A}k$, $V_{\rm A} = B/(4\pi\rho)^{1/2}$.

From the dispersion relation (23), it follows that the helicon is the transverse circularly polarized and damped wave in which the densities of the magnetic flux and the electron current undergo coherent oscillations in the plane perpendicular to the direction of propagation. In diffusion-free regime, $\Gamma_{\rm h} \ll 1$, one has

$$\omega_{\rm h} = \frac{\omega_{\rm c}}{\omega_{\rm p}^2} c^2 k^2 = 4.97 \times 10^{18} \frac{B}{n_{\rm e}} k^2. \tag{25}$$

The corresponding group velocity is given by

$$V_{\rm h} = \frac{2c^2\omega_{\rm c}}{\omega_{\rm p}^2} k \approx 9.94 \times 10^{18} \frac{B}{n_{\rm e}} k \,{\rm cm\,s^{-1}}. \tag{26}$$

Making use of (25) the latter formula can be represented in terms of $\omega$, as follows:

$$V_{\rm h} = \frac{2c\sqrt{\omega_{\rm c}}}{\omega_{\rm p}} \sqrt{\omega} \approx 4.46 \times 10^9 \sqrt{\frac{B}{n_{\rm e}}} \sqrt{\omega} \,{\rm cm\,s^{-1}}. \tag{27}$$

As a representative example, we take $\omega \approx 1\,{\rm s^{-1}}$, which is typical of pulsar activity. The average density of electrons and the magnetic field in the Galactic disc are estimated to be $n_{\rm e} \approx 0.03\,{\rm cm^{-3}}$ and $B \approx 10^{-5}$–$10^{-6}$ gauss, respectively (Lyne, Manchester & Taylor 1985). In the ISM that has the above parameters, the group velocity of helicons is $V_{\rm h} \approx 10^7$–$10^8\,{\rm cm\,s^{-1}}$ and their wavelength is $\lambda_{\rm h} = (2\pi/k) \approx 1000$ km. It is easy to check that the criterion of dissipation-free propagation of helicoidal magneto-electron wave, $\Gamma_{\rm h} = \nu_{\rm c}/\omega_{\rm c} \ll 1$, is fulfilled. Indeed, the cyclotron frequency $\omega_{\rm c}$, setting the upper limit for the frequency of the dissipative-free propagation of helicons, falls into the interval $10 < \omega_{\rm c} < 100\,{\rm s^{-1}}$, whereas the frequency of elastic collisions $\nu_{\rm c} \approx 10^{-2}$–$10^{-3}\,{\rm s^{-1}}$. Therefore, the helicons may propagate fairly freely throughout the ISM that has the above parameters. The helicons might be relevant to the interstellar scintillations of the pulsar signals. The latter effect is customarily attributed to the scattering of radio waves on fluctuations in electron density (Rickett 1990; Narayan 1992). These fluctuations exhibit features typical of turbulent motions whose dispersion relationship is extrapolated by a power spectrum (Sridhar & Goldreich 1994). From the above simple estimates it does not seem implausible that helicoidal magneto-electron waves might provide a contribution to the effect of interstellar scintillations of the pulsar radio signal.

## 4 APPLICATION TO MOLECULAR CLOUDS

From an extensive analysis of thermodynamic state of the interstellar medium in our Galaxy reported by Heiles & Kulkarni (1987), it follows that the warm diffusive clouds might be the regions of most dense accommodation of thermal electrons in which their density can attain a fairly high value: $n_{\rm e} \approx 1\,{\rm cm^{-3}}$ (Heiles et al. 2000). On the other hand, highly ionized H II regions of the warm interstellar medium occupy only 25 per cent of the Galactic volume (Heiles 1994). Therefore they make a significant contribution to the dispersion measure for only a small fraction of pulsars. The latter observation was made long ago by Manchester & Taylor (1977) and it led them to suggest that dispersing electrons can basically be located in denser interstellar clouds highly obscured for ionizing ultraviolet radiation and soft X-rays. However, if at some stage of the star formation the thermal electrons reside in the central region of a molecular cloud, then their presence would be very difficult to detect. In this case, highly coherent electron gas-dynamical processes resulting in observational consequences might enable indirect searches for the thermal electrons.

The evidence for the existence of large-scale motions in dark star-forming molecular clouds provides the widths of molecular lines. Therefore it is interesting to discuss a possible contribution of helicons to the broadening of molecular lines detected from dark interstellar clouds. By inspecting a possible effect of helicons on the widths of molecular lines for the former, we notice that in a typical dark molecular cloud $\omega_{\rm c} \approx 10^2\,{\rm s^{-1}}$ and $\nu_{\rm c} \approx 10^{-4}\,{\rm s^{-1}}$. In dark molecular clouds this latter frequency is dominated by electron–neutral collisions $\nu_{\rm c} \approx \nu_{\rm en} \approx 10^{-7} n_{\rm H_2}\,{\rm s^{-1}}$, where $n_{\rm H_2} \approx 10^3\,{\rm cm^{-3}}$ is the particle density of $H_2$ molecules (Mouschovias 1987). So that the criterion of dissipation-free propagation of helicons $\Gamma = \nu_{\rm c}/\omega_{\rm c} \ll 1$ is well justified, and its validity remains quite robust to the changes in $\nu_{\rm c}$ up to $\nu_{\rm c} \approx 100\,{\rm s^{-1}}$. The last statement is illustrated in Fig. 2, where we plot $\Gamma_{\rm h}$ as a function of $\nu_{\rm c}$. By taking the group velocity of the helicons $V_{\rm h}$ to be equal to the velocity dispersion measured for molecular lines, $V \approx 0.3$–$5.0\,{\rm km\,s^{-1}}$, one finds that the wavelength of the intercloud

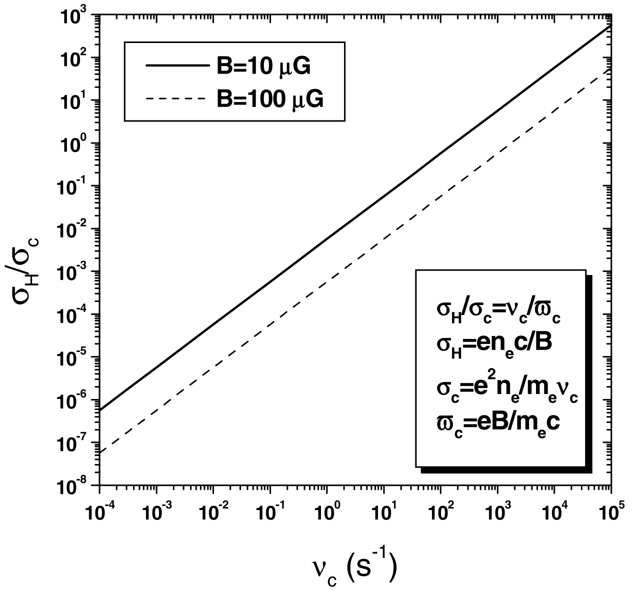


**Figure 2.** The ratio of the Hall conductivity $\sigma_{\mathrm{H}}$ to the Drude conductivity $\sigma_{\mathrm{c}}$ with parameters typical of dark molecular clouds.

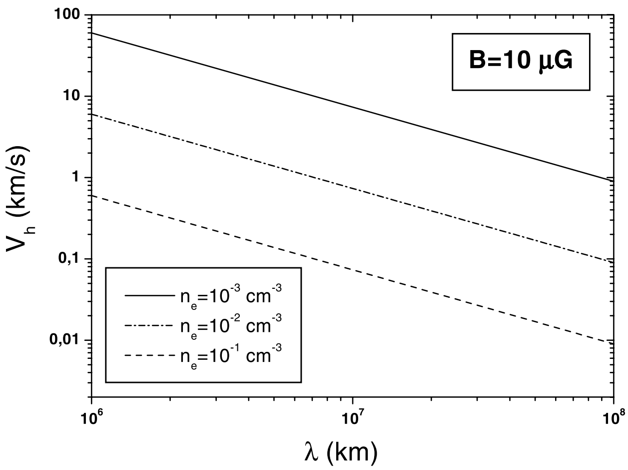


**Figure 3.** The group velocity $V_{\mathrm{h}}$ of helicoidal magneto-electron wave versus its wavelength $\lambda$.

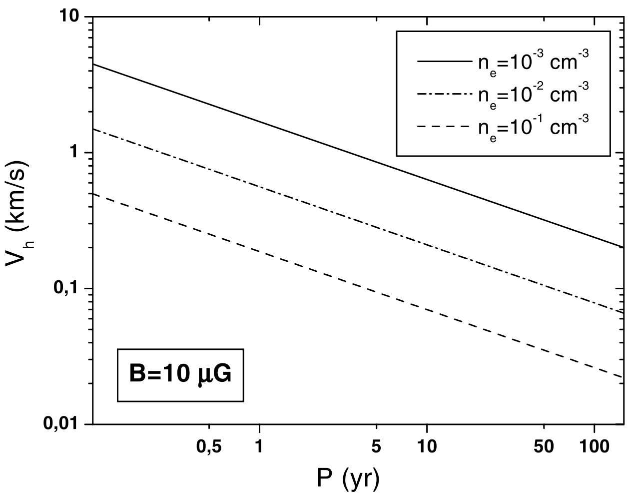


**Figure 4.** The group velocity $V_{\mathrm{h}}$ of helicoidal wave as a function of period of magneto-electron oscillations $P_{\mathrm{h}}$.

helicon is $\lambda_{\mathrm{h}} \approx 10^{12}-10^{13}$ cm. This space-scale is much less than the linear size of clouds, $L \approx 10^{17}$ cm. For the same velocity, the period of oscillations of electron flow in the helicoidal magneto-electron wave falls into the interval $P_{\mathrm{h}} \approx 0.1-10$ yr. This time-scale is much shorter than time of Ohmic decay $\tau_{\mathrm{Ohm}} = (4\pi\sigma_{\mathrm{c}}L^2)/c^2$ of the magnetic field (the latter is even larger than the Hubble time) and lifetime of molecular clouds. In Fig. 3 we plot the group velocity of helicons as a function of their wavelength and in Fig. 4 as a function of the period of magneto-electron oscillations. The above estimates show that the intercloud medium can transmit the helicoidal magneto-electron waves without significant attenuation in the regime of the ISM motions when the effects of ambipolar diffusion are heavily suppressed. We therefore conjuncture that they can be responsible for the broadening of molecular lines.

## 5 SUMMARY

Understanding gas-dynamical processes governing the structure and the evolution of dense molecular clouds is one of the outstanding challenges in the current development of star formation astrophysics. While the central role of magnetic fields in such processes was recognized many years ago, the major uncertainties regarding the motions follow from inadequate knowledge of the material composition of the intercloud medium. Over the years, convincing evidence has been obtained that shows that the composition of dark molecular clouds is dominated by molecular hydrogen with some admixture of OH and CO molecules whose linewidths are found to exhibit the supersonic character of intercloud motions. The fact that the linewidths cannot be explained as a result of the propagation of isothermal sound waves has served as an impetus in searching for alternative models of interstellar gas dynamics and has led to the hypothesis of the presence in dark molecular clouds of a sizable fraction of charged particles (primarily electrons and ions) whose collective flows are strongly coupled with the intercloud magnetic field. On the assumptions that the magnetic field causes both electrons and ions to move with equal velocities and then friction causes the neutral molecules to follow the ions with the same velocity, the model of single-component magnetohydrodynamics has been extensively exploited in interpreting supersonic broadening of molecular lines in terms of hydromagnetic waves of the Alfvén type (e.g. Arons & Max 1975; Myers & Goodman 1988; Mouschovias & Psaltis 1995; Zweibel & McKee 1995; Gammie & Ostriker 1995; Padoan & Nordlund 1999). On average, the model provides a fairly reasonable account of data in the CO regions of clouds where the temperature and the ionization factor are pretty high.

Together with this, recent Zeeman measurements of magnetic fields in dense cores of molecular clouds, highly obscured from ionizing ultraviolet radiation, have revealed a predominately sub-Alfvénic character for intercloud motions (Crutcher 1999). The latter circumstance can be regarded as an indication that the composition and the character of the motions in cores of the molecular clouds might be quite different from those which are implied by using the single-component MHD model of interstellar gas dynamics. With this in mind, in recent work (Yang & Bastrukov 2000; Bastrukov & Yang 2000) we investigated a model of non-MHD type. Motivated by the observable filamentary structure of some of the dark molecular clouds, we argued that the filaments could be regarded as a manifestation of a super-paramagnetic state of the gas–dust ISM considered long ago by Jones & Spitzer (1967) in the context of the starlight polarization problem. This sort of magnetically polarized, poorly conducting soft matter can be thought of as gas-based ferrocolloid (consisting of tiny ferromagnetic grains suspended in the dense gas of molecular hydrogen) capable of sustaining a long-range magnetic chains extending along the intercloud magnetic fields. Having supposed that the motions of the Jones–Spitzer matter are governed by equations of magnetoelastodynamics, we found that the ferrocolloidal interstellar medium can transmit perturbations by shear magnetomechanical waves propagating with a sub-Alfvénic group velocity in accordance with observations (Crutcher 1999).

In the meantime, it has been argued by several authors that the motions of the ISM in star-forming molecular clouds can pass the regime in which Hall conductivity may become important (Nakano & Umebayashi 1986; Wardle 1998; Rudakov et al. 2001). In particular, it is shown in a recent paper (Wardle & Ng 1999) that the Hall conductivity can essentially affect propagation of Alfvén waves in dense, weakly ionized molecular gas. Continuing the investigation in this direction, we have explored here a model of a pure electron interstellar gas dynamics; the propagation of spiral magneto-electron waves which owe their existence to the Hall drift of magnetic flux by thermal electrons. The basic inference of this model is that in dark molecular clouds the helicons suffer negligible damping by Ohmic conductivity. A similar conclusion regarding the helicons in a dusty space plasma has recently been reached by Rudakov et al. (2001). Our numerical estimates for the group velocity of the helicons suggest that these waves could be responsible for the broadening of molecular linewidths detected from dark star-forming clouds or, at least, provide a sizable contribution to this effect.

## ACKNOWLEDGMENTS

The work was partially supported by Korea Research Foundation Grant (KRF-2001-041-D00052).

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