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# DUSTY MOLECULAR CLOUD COLLAPSE IN THE PRESENCE OF ALFVÉN WAVES

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## ABSTRACT

It has been shown that magnetic fields play an important role in the stability of molecular clouds, mainly perpendicular to the field direction. However, in the parallel direction the stability is a serious problem still to be explained. Interstellar turbulence may allow the generation of Alfvén waves that propagate through the clouds in the magnetic field direction. These regions also present great quantities of dust particles, which can give rise to new wave modes or modify the preexisting ones. The dust-cyclotron damping affects the Alfvén wave propagation near the dust-cyclotron frequency. On the other hand, the clouds present different grain sizes, which carry different charges. In this sense, a dust particle distribution has several dust-cyclotron frequencies, and it will affect a broad band of wave frequencies. In this case, the energy transfer to the gas is more efficient than in the case where the ion-cyclotron damping is considered alone. This effect becomes more important if a power-law spectrum is considered for the wave energy flux, since the major part of the energy is concentrated in low-frequency waves. In this work we calculate the dust-cyclotron damping in a dusty and magnetized dwarf molecular cloud, and determine the changes in the Alfvén wave flux. Then we use these results to study the gravitational stability of the cloud. We show that, considering the presence of charged dust particles, the wave flux is rapidly damped through dust-cyclotron damping. Then the wave pressure acts in a small length scale and cannot explain the observable cloud sizes, but can explain the existence of small and dense cores.

*Keywords:* dust, extinction — ISM: clouds — ISM: magnetic fields — ISM: molecules — MHD — plasmas — waves

## 1. INTRODUCTION

There are in the literature several works concerning the mechanical stability of dwarf molecular clouds (DMCs). These clouds have masses of less than $10^3\ M_\odot$ in regions of 2–5 pc radius, and temperatures of $\sim$10–20 K (Shu, Adams, & Lizano 1987; Evans 1999). It is believed that these objects can live more than $10^8$ yr in equilibrium. A cloud with only thermal support will collapse if the mass exceeds the Jeans mass. This fact seems to be a problem in DMCs, considering that the Jeans mass of an isothermal gas is

$$M_{\rm J} \equiv \rho_0 \lambda_{\rm J}^3 = \left(\frac{\pi}{G}\right)^{3/2} \rho_0^{-1/2} c_s^3 \ , \qquad (1)$$

where $\rho_0$ is the mass density and $c_s$ is the sound velocity. In the case of DMCs, $M_{\rm J}$ is a few solar masses, which is much smaller than the cloud mass. Similarly, the free-fall collapse time,

$$t_{\rm ff} = \left(\frac{3\pi}{32 G \rho_0}\right)^{1/2} , \qquad (2)$$

is $\sim 10^6$ yr, which is much smaller than the lifetime of these objects. As a consequence, the thermal pressure alone cannot explain the stability of these clouds. Several additional support mechanisms have been proposed, such as magnetic fields (e.g., Chandrasekhar & Fermi 1953), rotation (Field 1978), and turbulence (Norman & Silk 1980; Bonazzola et al. 1987).

Typical magnetic fields of $\sim\mu$G (Crutcher 1999) can increase $M_{\rm J}$ to the expected values. However, the magnetic pressure acts against the collapse only in the perpendicular direction of the magnetic field. Turbulence can excite the generation of MHD waves, which can propagate along the field lines, adding an extra pressure term in the parallel direction (McKee & Zweibel 1995; Gammie & Ostriker 1996; Martin, Heyvaerts, & Priest 1997). Martin et al. (1997) showed that an Alfvén wave flux can support the cloud collapse in the direction parallel to the magnetic field, but for that it would be necessary to have a great amount of magnetic energy concentrated in a weakly damped wave spectrum range.

In the literature several damping mechanisms for the Alfvén waves have been proposed. In particular, Martin et al. (1997), studying the changes on the DMCs stability caused by the presence of Alfvén waves propagating along the magnetic field, considered the damping of these waves as a result of the ion-neutral collisions, which is weak for low-frequency waves. Zweibel & Josafatsson (1983) also showed that if only ion-neutral collisional and nonlinear damping mechanisms are considered, the Alfvén wave mode is weakly damped in DMCs. In this case, the wave flux may reach the edges of the cloud and support the gas against gravity. However, if strong damping mechanisms take place, the wave flux will be damped suddenly, and will not reach the edges of the cloud.

The physical conditions of DMCs suggest the existence of charged dust particles resulting from collisions with electrons of the plasma. Chhajlani & Parihar (1994) showed that charged dust particles affect the gravitational stability, changing the Jeans criterion in both the perpendicular and parallel directions to the field. In another view, once charged, these particles will suffer the influence of the magnetic field that gives rise to a cyclotron frequency and a resonance associated with them. For the ions, this resonance occurs in a narrow range of higher frequencies, being unimportant in the systems under consideration. On the other hand, the dust cyclotron resonance occurs in low

frequencies, and it can be an important damping mechanism for the waves propagating in molecular clouds. Mathis, Rumple, & Nordsiek (1977, hereafter MRN) observed and fitted the interstellar medium (ISM) extinction to a distribution of different dust particles. In particular, the dust particles size distribution seems to be a power-law spectrum, $f(a) = Ca^{-p}$, with $p \sim 3$–4, for different dust compositions. Tripathi & Sharma (1996) and Cramer, Verheest, & Vladimirov (2002) showed that a size distribution of charged dust particles can modify the dispersion relation of Alfvén waves and give rise to a wave-resonant damping in the frequencies coincident with the dust-cyclotron frequency.

In this work we present a model in which a flux of waves propagating in a DMC is damped as a result of resonant interaction with dust charged particles, and we analyze the consequences for the cloud stability. We proceed as follows. In § 2, we describe the wave dispersion relation modified by the presence of charged dust. In § 3, we describe the model for the cloud stability and present the results. Finally, we draw our conclusions.

## 2. ALFVÉN WAVES PROPAGATING IN A DUSTY PLASMA

The propagation and damping of Alfvén waves in dusty plasma has been considered by many authors (e.g., Pillip et al. 1987; Mendis & Rosenberg 1992; Shukla 1992). Although the number of dust particles is smaller than the number of ions, the process of dust charging is efficient, and these particles can obtain charges on the order of $q_d \sim 10^0$–$10^3$ $e^-$ in astrophysical media (Goertz 1989; Mendis & Rosenberg 1994). Dust particles modify the plasma behavior in different ways. In particular, charged dust particles introduce a cutoff in the Alfvén wave in the dust cyclotron frequency. If a distribution of grain sizes is considered, we obtain a large band of resonance frequencies instead of a single one.

According to MRN, we can describe the distribution of grain sizes by the function $f(a) = Ca^{-p}$, where $a$ is a dimensionless radius, defined as $a = r/r_{\min}$, where $r_{\min} < r < r_{\max}$, and $C = (p-1)/(1 - a_m^{1-p})$. We define $a_m \equiv (r_{\max}/r_{\min})$ as the ratio of maximum and minimum dust radii. Observationally, the parameter $p$ depends on the dust constituent and on the environment. Typically, for dust particles of $0.005\ \mu\mathrm{m} < r < 1\ \mu\mathrm{m}$, we have $3 \leqslant p \leqslant 4$. In this work we consider $p = 4$, as used by Cramer et al. (2002), and, in this case, $C = 3/(1 - a_m^{-3})$.

The wave propagation in dusty plasma is modified, and some new and interesting effects take place (Wardle & Ng 1999; Cramer 2001). The dispersion relation of the Alfvén waves with frequencies smaller than the ion cyclotron frequency, considering constant charged dust particles in a neutral and cold dusty plasma, is given by (Cramer et al. 2002)

$$k_z^2 = u_1 \pm u_2 \ , \tag{3}$$

where

$$u_1 = \frac{\omega^2 \Omega_{i0}^2}{v_{\mathrm{A}}^2 (\Omega_{i0}^2 - \omega^2)} + \frac{\omega^2 \Omega_{d,\max}^2}{s v_{\mathrm{A},d}^2} \int_1^{a_m} \frac{f(a)}{a\left[(\Omega_{d,\max}^2/a^4) - \omega^2\right]}\, da \ , \tag{4}$$

and

$$u_2 = \frac{\omega^3 \Omega_{i0}}{v_{\mathrm{A}}^2 (\Omega_{i0}^2 - \omega^2)} + \frac{\omega^3 \Omega_{d,\max}}{s v_{\mathrm{A},d}^2} \int_1^{a_m} \frac{f(a)}{(\Omega_{d,\max}^2/a^4) - \omega^2}\, da \ , \tag{5}$$

where $s = C \ln a_m$, $B_0$ is the external mean magnetic field, $\omega$ is the angular wave frequency, $v_{\mathrm{A}} = B_0/(4\pi\rho_i)^{1/2}$ is the Alfvén speed in terms of the ion density, $v_{\mathrm{A},d} = B_0/(4\pi\rho_d)^{1/2}$ is the Alfvén speed, $\rho_d$ is the dust mass density, $\Omega_{i0} = q_i B_0/m_i c$ is the ion cyclotron frequency, and $\Omega_{d,\max} = q_d B_0/m_d c$ is the maximum dust cyclotron frequency (i.e., for the minimum dust radius). The mean grain particle charge can be obtained for each dust radius considering charging current equilibrium over dust surface. The equilibrium equation, considering a Maxwellian distribution of velocities, is given by

$$\frac{\omega_{pi}^2}{v_{Ti}} \left(1 + \frac{q_d q_e}{r k_{\mathrm{B}} T}\right) = \frac{\omega_{pe}^2}{v_{Te}} e^{-(q_d q_e)/(r k_{\mathrm{B}} T)} \ , \tag{6}$$

where $\omega_{p\beta}$ is the plasma frequency and $v_{T\beta}$ is the thermal velocity of the $\beta$ species.

The left-hand polarized wave (−) interacts with ions, and is not affected by the negatively charged dust particles resonance. The right-hand polarized wave (+) is the mode damped by the dust resonance. In the case of $\Omega_{d,\max}/a_m^2 < \omega < \Omega_{d,\max}$, the integral in the particles radii has singularities, whose residues give the complex part of the wavenumber ($k_i$), and that leads to the dust-cyclotron damping of the waves. If dust density vanishes (i.e., considering a dustless plasma), $v_{\mathrm{A},i}/v_{\mathrm{A},d} \propto (\rho_d/\rho_i)^{1/2} = 0$. By that, multiplying equations (3), (4), and (5) by the ion Alfvén velocity ($v_{\mathrm{A}}$), the term that gives the imaginary part of the wavenumber will vanishes, and equation (3) reverts to the well-known dispersion relation for ion and electrons plasma.

Cramer et al. (2002) solved equations (3)–(5) using $a_m = 1.1$. However, in the interstellar gas, this ratio is $\sim 10^2$. We performed same calculations, including the determination of mean dust particle charge, using equations (3)–(6). To illustrate how this parameter influences the wave dispersion relation, we plotted in Figure 1 the real and imaginary parts of the wavenumber, using different values for the $a_m$ parameter.

In Figure 1, we plot the solution of the equation (3) using as a parameter the dust mass density, given by $\rho_{\mathrm{H}_2}/\rho_d \sim 200$ (Kramer et al. 2003; Perna, Lazzati, & Fiore 2003; Spitzer 1968). In Figure 1*a* we have the real part of the wavenumber for $a_m = 1.1$ (*solid line*), used also by Cramer et al. (2002), and $a_m = 1.3$ (*dotted line*), chosen to illustrate how a small change in $a_m$ induces an important modification in the dispersion relation. In Figure 1*b* we show the imaginary part of the wavenumber for $a_m = 1.1$ (*solid line*), and $a_m = 1.3$ (*dotted line*). For $a_m = 1.1$, the resonance band occurs in the range $0.83 < \omega/\Omega_{d,\max} < 1$, and in the case of $a_m = 1.3$ the resonance band occurs for $0.59 < \omega/\Omega_{d,\max} < 1$. Note that the range of resonant frequencies is then proportional to $a_m^2$. In the interstellar medium we have $a_m > 100$, and the expected resonance band would be in the range $0.0001 < \omega/\Omega_{d,\max} < 1$, affecting almost all low-frequency spectra. For this reason, it is interesting to study the effects

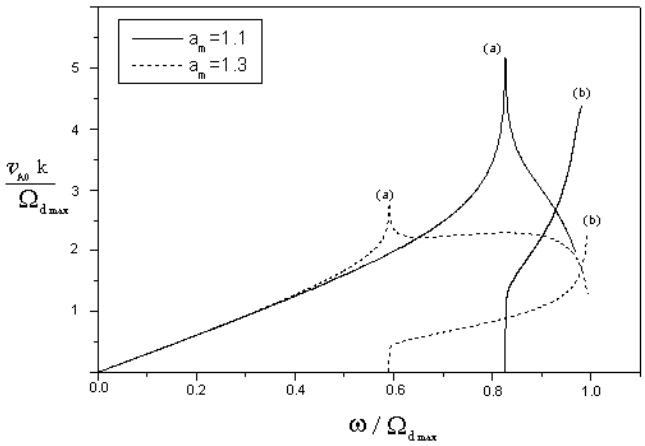


FIG. 1.—(*a*) Real part of the wavenumber for $a_m = 1.1$ (*solid line*) and $a_m = 1.3$ (*dotted line*). (*b*) The imaginary part of the wavenumber for $a_m = 1.1$ (*solid line*) and $a_m = 1.3$ (*dotted line*).

of the dust cyclotron damping on the Alfvén wave propagation, and the consequences for the mechanical stability of DMCs due to the presence of these particles.

## 3. THE CLOUD STABILITY

Following the model proposed by Martin et al. (1997), we study the case of a flattened cloud, permeated by an uniform magnetic field $\boldsymbol{B} = B_0\hat{z} + \delta B\hat{x}$, whose perturbation $\delta B$ is an Alfvén wave propagating ($\boldsymbol{k}$) in the direction parallel to the magnetic field. The wave pressure allows another cloud support mechanism, as shown in the scheme in Figure 2. We considered that $\delta B \ll B_0$, so that the linear approach can be used.

The momentum equation of a self-gravitating plasma, including magnetic pressure, is given by

$$\rho\frac{\partial \boldsymbol{u}}{\partial t} + \rho(\boldsymbol{u}\cdot\nabla)\boldsymbol{u} = -\nabla P + (\boldsymbol{B}\cdot\nabla)\frac{\boldsymbol{B}}{4\pi} - \nabla\left(\frac{B^2}{8\pi}\right) + \rho\boldsymbol{g}\ , \quad (7)$$

where $\boldsymbol{u}$ is the velocity, $P$ is the thermal pressure of the gas, $\rho$ is the mass density, $\boldsymbol{B}$ is the magnetic field, and $\boldsymbol{g}$ is the gravity acceleration.

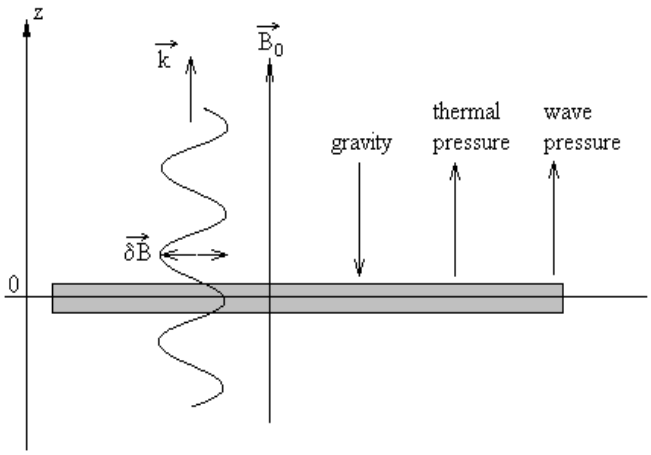


FIG. 2.—In this scheme, we show the propagation direction of the Alfvén waves and the way as they increase the cloud support against gravity.

In the perpendicular direction to $\boldsymbol{B}_0$, the magnetic field pressure is sufficient to prevent the gravitational collapse. For this reason, we study the stability in the $z$-direction. Considering the model described in Figure 2, the temporal mean of the momentum equation (7) for a cloud in mechanical equilibrium can be written by

$$-\nabla P - \nabla\varepsilon + \rho\boldsymbol{g} = 0\ , \quad (8)$$

where $\varepsilon = \langle\delta B^2\rangle/8\pi$ is the magnetic energy density of the MHD waves propagating in the parallel direction to $\boldsymbol{B}_0$.

As we will see in the following section, the waves that are affected have frequencies near the dust-cyclotron frequency, which leads to wavelengths of $\sim 10^{15}$ cm. In this case, since the waves have a wavelength smaller than the system scales ($\sim$0.1 pc), the WKB approach can be used, and the energy conservation equation will be given by

$$\nabla \ln(\varepsilon v_{\rm A}) = -L^{-1}\ , \quad (9)$$

where $L$ is the wave-damping length, which is related to the imaginary part of the wavenumber ($k_i$), determined in the previous section, by $L = 2\pi/k_i$.

The system of differential equations is completed with the Poisson equation

$$\nabla\cdot\boldsymbol{g} = 4\pi G\rho\ , \quad (10)$$

where $G$ is the gravitational constant.

Tu, Roberts, & Goldstein (1989) observed an Alfvén wave spectrum propagating in the solar wind, and inferred the power-law spectrum

$$\Phi_{\rm A}(\omega) = \Phi_{\rm A}(\omega_0)\left(\frac{\omega}{\omega_0}\right)^{-\alpha}\ , \quad (11)$$

where $\alpha \sim 0.6$ and $\Phi_{\rm A}(\omega_0)$ is the Alfvén wave flux at the frequency $\omega_0$.

The origin of the Alfvén wave spectrum is unknown, and many possibilities have been proposed to explain it, e.g., turbulence, magnetic field annihilation, and convection. We will suppose that some internal process in DMCs generates magnetic perturbations, which act as the origin of a spectrum of the Alfvén waves similar to that observed in the solar wind. The total flux is given by

$$\Phi_{\rm tot} = \int_{\omega_{\rm min}}^{\omega_{\rm max}} \Phi_{\rm A}(\omega)\, d\omega\ . \quad (12)$$

The relation between the total flux and the wave energy density is $\varepsilon = \Phi_{\rm tot}/v_{\rm A}$, and it is related to the thermal energy density of the gas ($U_{\rm int}$) by the parameter $\Lambda = \varepsilon/U_{\rm int}$. Thus, for a particular choice of the free parameter, $\Phi_{\rm A}(\omega_0)$, we calculate the total flux and the wave energy density, which is related to the internal energy density by $\Lambda$.

In the following subsections we describe the cloud stability, using the solutions of equations (8)–(10), considering two cases: (1) when there is no damping of the Alfvén waves, and (2) when the dust-cyclotron damping is considered for different $\Lambda$ values. Low $\Lambda$ values guarantee that the linear approach can be used. Typically, the ratio of gas pressure to the magnetic pressure, $\beta = P_g/\left(B_0^2/8\pi\right)$, assumes low values for molecular clouds ($\beta \sim 0.04$; Crutcher 1999; Sigalotti & Klapp 2000), implying that magnetic fields are extremely important in these regions. If one assumes a high flux of Alfvén waves, i.e., $\Lambda > 3$ (as done by Martin et al. 1997), the

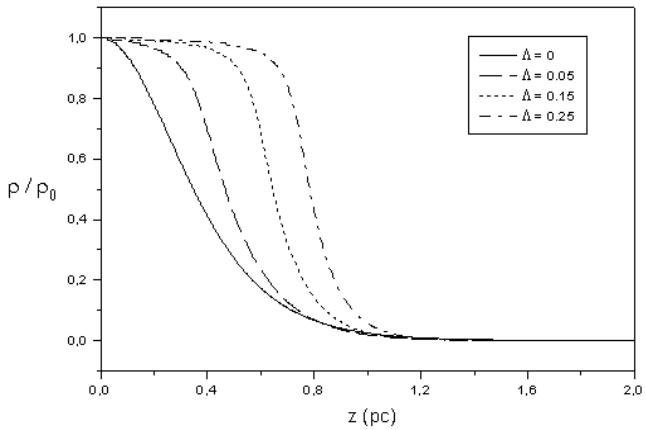


FIG. 3.—Cloud density profile as a function of distance for different values of the parameter $\Lambda$ for waves without damping. The solid line represents the situation without Alfvénic support, and the dashed, dotted, and dot-dashed lines represent the cases for $\Lambda = 0.05$, 0.15, and 0.25, respectively.

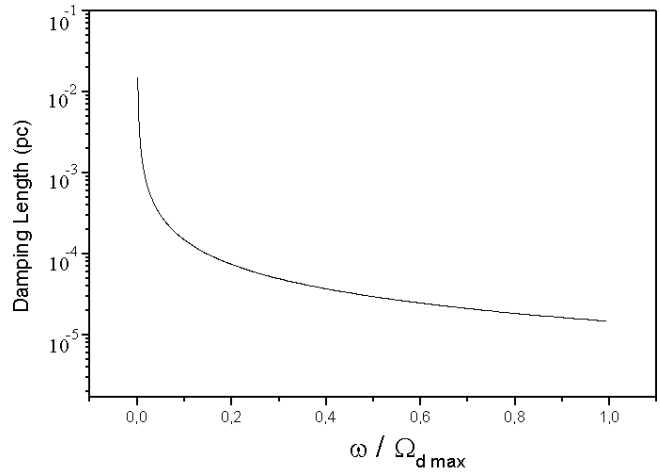


FIG. 4.—Wave dust cyclotron damping length as function of wave frequency for molecular cloud parameters used in § 2, considering a number density of the dwarf molecular cloud $n_0 = 10^4$ cm$^{-3}$, temperature $T = 20$ K, and mean magnetic field $B_0 = 10\ \mu$G.

ratio of the Alfvén wave amplitude to the mean magnetic field ($\eta = \delta B/B_0$) will be greater than 0.1, and in this case the linear approximation is no more valid.

### 3.1. *Cloud Stability: Alfvénic Support without Damping*

If there is no wave damping, $L^{-1} \to 0$, the wave energy density ($\varepsilon$), given by equation (9), reduces to $\varepsilon(z) = \varepsilon(z = 0)(\rho/\rho_0)^{1/2}$. In this case, a gradient in density produces a gradient in $\varepsilon$, and the latter acts as a support against the collapse of the cloud. Substituting this expression in equation (8), and also using equation (10), the density profile solution can be obtained. The local parameters used are the central number density of the dwarf molecular cloud $n_0 = 10^4$ cm$^{-3}$, temperature $T = 20$ K, and mean magnetic field $B_0 = 10\ \mu$G (Evans 1999). The solid line in Figure 3-shows the density profile in the case without Alfvénic support ($\Lambda = 0$), and the other plots represent equilibrium with Alfvénic support for three different $\Lambda$ values: $\Lambda = 0.05, 0.15$, and 0.25.

Figure 3 shows that the equilibrium cloud size increases as the energy density of the waves ($\varepsilon$) propagating through the cloud increases, in accordance with Martin et al. (1997). This indicates that the observed properties of these objects could be explained by an Alfvén waves flux. However, if we consider the wave damping, this result is modified, as we show in § 3.2.

### 3.2. *Cloud Stability: Alfvénic Support with Damping*

In a more realistic model, it is necessary to consider the wave propagation in a dusty medium, whose dust particles are charged. In this case, the dust-cyclotron damping treated in § 2 takes place. Considering the same parameters used in § 3.1, the calculation of equation (6) gives, for the cloud parameters used in the previous section, a mean dust charge of $\bar{q}_d \cong -1\ e^-$. Using the dust-cyclotron damping already described, and introducing equation (11) into equation (9), the modifications in the energy flux spectrum along the cloud $z$-direction can be obtained. The damping length as a function of the wave frequency is given in Figure 4. The figure shows that the whole resonance band is damped within 0.1 pc. This effect is even stronger for lower dust particles, which have higher resonance frequencies, and the damping length is $\sim 10^{-4}$ pc. The Alfvén wave spectrum, modified as the waves propagate through the cloud, is shown in Figure 5.

In Figure 5 we note that the waves flux, given by equation (11), is damped in the frequency range of dust-cyclotron resonance. The waves with frequencies coincident with the dust-cyclotron frequencies are damped ($\omega \sim \Omega_{d,\max}$). We also note that the frequency band is almost completely damped up to $z \sim 10^{-2}$ pc. In the calculations we used in equation (11), $\alpha = 0.6$. The choice of this parameter does not change our conclusions, since it just represents how energy is concentrated in the frequency spectrum. If $\alpha$ is too large, less energy is carried by high-frequency waves, while most of the energy would be carried by low-frequency waves, which continue to be damped within $z \sim 10^{-2}$ pc.

The cloud density profile, considering wave damping, can be obtained by the solution of equations (8)–(12), and it is shown in Figure 6. The dotted line shows the density profile in the case without Alfvénic support ($\Lambda = 0$), and the others represent equilibrium with Alfvénic support including the

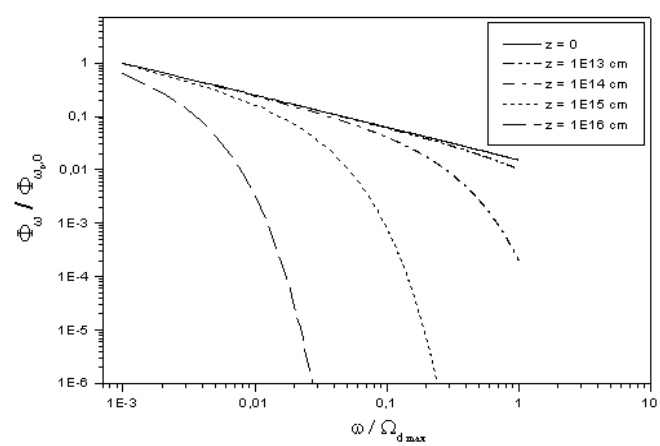


FIG. 5.—Wave power spectrum, damped by dust-cyclotron resonance, for different cloud locations ($z$) in the cloud.

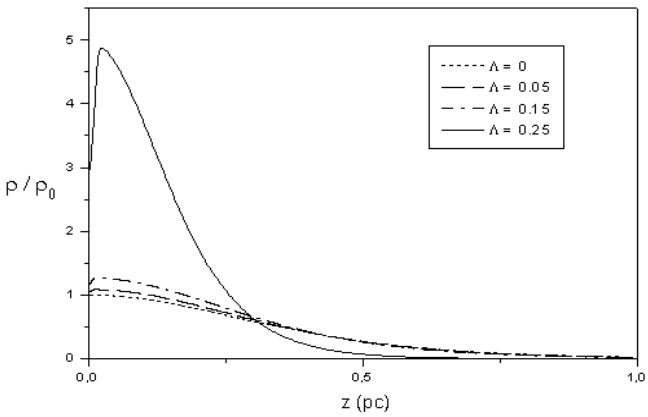


FIG. 6.—Cloud density profile as a function of distance for different values of the parameter $\Lambda$, including the wave damping. Dotted line represents equilibrium without Alfvénic support, and the dashed, dot-dashed, and solid lines represent the cases of $\Lambda = 0.05$, 0.15, and 0.25, respectively.

damping mechanism for three different $\Lambda$ values: $\Lambda = 0.05$, 0.15, and 0.25.

As we can see in Figure 6, the waves are damped for $z < 1$ pc and cannot support the edges of molecular clouds. This result can be compared to Figure 3 of Martin et al. (1997), where a weak Alfvén wave damping allows the stability of the cloud up to several parsecs. In this sense, the damped Alfvénic support cannot be used to explain the observed cloud sizes of $z \sim 1$–5 pc, unless one assumes that the waves are being generated along the whole cloud. However, it is important to note that the sudden damping of the wave flux results in compact and denser cloud cores. In this case, dense and compact cores, or even cloud clumpiness, already observed in DMCs, e.g., by Snell et al. (1984) and Loren, Sandqvist, & Wooten (1983), could be explained.

## 4. CONCLUSIONS

Considering typical dwarf molecular clouds with number density $n_{H_2} \sim 10^4$ cm$^{-3}$ and temperature $T \sim 20$ K, the corresponding Jeans mass is $M_J \sim 3\ M_\odot$. If this result is compared to the observed cloud masses $M \leq 100\ M_\odot$, we note that it is necessary to have an additional mechanism acting together with thermal pressure to support the cloud against its own gravity. Magnetic field of $\sim\mu$G has been observed in these regions, which can yield an extra pressure term to keep the stability perpendicular to the field lines. However, for the direction parallel to the magnetic field lines, where there is no pressure from the mean magnetic field, other mechanisms are necessary to support the cloud. Turbulence can excite MHD waves; in particular, the uncompressive Alfvén wave mode that can propagate along the magnetic field lines. It is believed that these waves are slowly damped in molecular clouds. In this case, we show that they can add a wave pressure term and support these clouds.

In a more realistic model, we use the fact that these clouds also present a great quantity of charged dust particles that suffer the influence of the magnetic field. These particles have a gyrofrequency that can give rise to a dust-cyclotron resonance with the Alfvén wave's frequency (Tripathi & Sharma 1996; Cramer et al. 2002). In this interaction the wave is damped and a gradient in the wave flux is established. In this work we have shown that, when wave damping is not considered, the wave flux can support the cloud against gravity, preventing its collapse, as also pointed out by Martin et al. (1997). On the other hand, considering the existence of charged dust particles, the waves are strongly damped by dust cyclotron damping. Taking into account this wave damping, discussed by Cramer et al. (2002), the flux is dissipated suddenly (in a region $\ll 1$ pc), leading to the formation of a compact and dense core. In this case, the waves could not reach the outer layers of the cloud, and if this is so, they could not be used to explain the size of these objects, although they could still be used to inhibit star formation.

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