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Solar low-ℓ p-mode damping by MHD turbulence

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Abstract. The linewidths of solar p-mode oscillations are known to change over a solar cycle. In this paper we adopt a simple model of time-dependent magnetohydrodynamic (MHD) turbulence in the solar convective zone to examine the effects of a fluctuating magnetic field on damping of solar low-ℓ p-modes, and find that the damping due to the magnetic perturbation increases with the strength of magnetic fields, and that its temporal behavior closely follows the phase of the synthetic solar activity cycle. The results confirm a variation of the damping between the minimum and the maximum of solar activity cycle. Our analysis indicates that the linewidths of modes are sensitive to the effect of turbulent magnetic fields, and might be used as a potential tool for probing the structure and dynamic changes inside the Sun.

Key words. Sun: helioseismology

1. Introduction

The convection zone is of crucial importance for the excitation and damping of solar p-modes (Stein & Nordlund 1998). The study of mode energy, damping and related time scales contributes very much to the understanding of this particular region of the Sun. If the modes are stochastically excited and instrinsically damped, the linewidths directly measure the damping rates and provide immediate tests of the stochastic excitation theory and its parameters. Therefore, the investigation of linewidths for p-mode oscillations would be extremely powerful probes of the solar interior.

In general, all measurements of linewidths from different instruments display the same behavior, presenting that mode line width at a fixed degree increases with mode frequency, except for the familiar "plateau" between 2.5 and 3.1 mHz with a dip near 2.9 mHz (Libbrecht et al. 1990; Elsworth et al. 1990; Tomczyk et al. 1995; Hill et al. 1996; Chaplin et al. 1997; Schou 1998; Rabello-Soares et al. 1999; Roca-Cortés et al. 1999). However, recent observations have convincingly shown that linewidths for the modes increase due to magnetic activity (Jefferies et al. 1991; Chaplin et al. 2000; Komm et al. 2000a, Komm et al. 2000b; Gelly et al. 2002; Howe et al. 2003).

To date, the predictions of theories of damping of the solar oscillations have been fitted to compare better with observations (Gough 1977; Christensen-Dalsgaard & Frandsen 1983; Christensen-Dalsgaard 1989; Gough 1990; Balmforth 1992; Goldreich et al. 1994; Houdek et al. 1999), but they do not explain the variation of linewidths for p-modes with increasing magnetic activity. This disagreement means that there might exist significant uncertainty in the physics of the Sun. Very recently, Houdek et al. (2001) attempted to test the effect of systematic changes the shapes of the convection granules on the damping of the modes, and found reasonable agreement with the observations. The main aim of this paper is to investigate the influence of magnetic fields on the damping of oscillation modes.

Solar p-mode linewidths are related to non-adiabatic effects, magnetic perturbations and turbulent processes. In this paper, it is assumed that only the important effects of turbulent magnetic fields are included in the equations, while all other effects are neglected, therefore, the magnetic perturbations can be considered as a first approximation of the dynamic motions to the steady state. In Sect. 2, the mathematical description of damping of oscillations with magnetic field fluctuations is derived in detail. We give a more realistic model for turbulent magnetic fields, in Sect. 3, including an incorporation of a physically meaningful description of the spatial and temporal spectrum of the fluctuating magnetic fields. We calculate the linewidths of p-modes due to the contribution of fluctuating magnetic fields and compare them with helioseismic data in Sect. 4, and summarize the main conclusions in Sect. 5.

2. Stability equations

2.1. The linear approximation

If there is no rotation, the magnetohydrodynamic equations describing the motions of an ideal fluid of total density ρ, pressure P, velocity vector $\boldsymbol{v}$, in the presence of a magnetic field $\boldsymbol{B}$, are given by (Unno et al. 1989)

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0, \tag{1}$$

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$$\frac{\partial \boldsymbol{v}}{\partial t} + (\boldsymbol{v}\cdot\nabla)\boldsymbol{v} = -\frac{1}{\rho}\nabla P + \frac{1}{4\pi\rho}(\nabla\times\boldsymbol{B})\times\boldsymbol{B} - \nabla\Phi + \boldsymbol{F}(\boldsymbol{u}), \tag{2}$$

where $\boldsymbol{B}$ satisfies the induction equation in the MHD approximation

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla\times(\boldsymbol{v}\times\boldsymbol{B}), \tag{3}$$

with Gauss's law

$$\nabla\cdot\boldsymbol{B} = 0, \tag{4}$$

and the gravitational potential Φ is determined by Poisson's equation

$$\nabla^2\Phi = -4\pi G\rho, \tag{5}$$

G being the gravitational constant. $\boldsymbol{F}(\boldsymbol{u})$ is the additional force which depends on the turbulent velocity $\boldsymbol{u}$.

We noted that the term of the Lorentz force in Eq. (2), with the help of Eq. (4), can be divided into a magnetic pressure and a magnetic tension stress

$$\begin{aligned}(\nabla\times\boldsymbol{B})\times\boldsymbol{B} &= (\boldsymbol{B}\cdot\nabla)\boldsymbol{B} + (\nabla\cdot\boldsymbol{B})\boldsymbol{B} - \frac{1}{2}\nabla B^2 \\ &= \nabla\cdot\left(\boldsymbol{B}\boldsymbol{B} - \frac{1}{2}B^2\right),\end{aligned} \tag{6}$$

therefore, substituting of Eq. (6) into Eq. (2), the motion equation becomes

$$\frac{\partial \boldsymbol{v}}{\partial t} + (\boldsymbol{v}\cdot\nabla)\boldsymbol{v} = -\frac{1}{\rho}\nabla(P+P_B) + \frac{1}{4\pi\rho}\nabla\cdot(\boldsymbol{B}\boldsymbol{B}) - \nabla\Phi + \boldsymbol{F}(\boldsymbol{u}), \tag{7}$$

where the magnetic pressure is defined as

$$P_B \equiv \frac{B^2}{8\pi}\cdot \tag{8}$$

Obviously, we assume that the ratio of the magnetic pressure to the thermal pressure $\left(\frac{P_B}{P}\right)$ is small with the helioseismic constraints on solar models (Gough 1996), thus P_B can be ignored in Eq. (7).

We consider the effects of velocity fields and magnetic fields on the equilibrium structure and on the oscillations as small perturbations. For Euler perturbations, the various physical quantities can be treated as the sum of an equilibrium value and a perturbation, that is

$$\rho = \rho_0 + \rho', \quad \boldsymbol{v} = \boldsymbol{v}_0 + \boldsymbol{v}', \quad P = P_0 + P', \quad \boldsymbol{B} = \boldsymbol{B}_0 + \boldsymbol{B}', \tag{9}$$

where the subscript "0" and the superscript "′" refer to equilibrium quantities and the perturbation quantities, respectively.

Substituting Eq. (9) into nonlinear Eqs. (1), (3) and (7), and neglecting terms with higher orders of perturbation values, noting that values at equilibrium fulfil the above equations, and assuming a solenoidal velocity field

$$(\boldsymbol{B}_0\cdot\triangledown)\boldsymbol{v}_0 - (\boldsymbol{v}_0\cdot\triangledown)\boldsymbol{B}_0 = 0, \tag{10}$$

we obtain linearized ideal MHD perturbation equations as

$$\frac{\partial\rho'}{\partial t} + \nabla\cdot(\rho_0\boldsymbol{v}') = 0, \tag{11}$$

$$\begin{aligned}\frac{\partial \boldsymbol{v}'}{\partial t} + (\boldsymbol{v}_0\cdot\nabla)\boldsymbol{v}' + (\boldsymbol{v}'\cdot\nabla)\boldsymbol{v}_0 = \\ -\frac{1}{\rho_0}\nabla\left(P' + \frac{\boldsymbol{B}_0\cdot\boldsymbol{B}'}{4\pi}\right) - \nabla\Phi' \\ + \frac{(\boldsymbol{B}_0\cdot\nabla)\boldsymbol{B}'}{4\pi\rho_0} - \frac{\rho'}{4\pi{\rho_0}^2}\nabla\cdot\mathfrak{B} + \boldsymbol{f}(\boldsymbol{u}),\end{aligned} \tag{12}$$

and the corresponding induction equation for the fluctuating magnetic field is

$$\frac{\partial \boldsymbol{B}'}{\partial t} = \nabla\times(\boldsymbol{v}'\times\boldsymbol{B}_0) + \nabla\times(\boldsymbol{v}_0\times\boldsymbol{B}'), \tag{13}$$

where the force $\boldsymbol{f}(\boldsymbol{u})$ is the perturbation of $\boldsymbol{F}(\boldsymbol{u})$, and the fluctuating magnetic tension stress is defined as

$$\mathfrak{B}_{ij} \equiv \left\langle B'_i(\boldsymbol{x}',t')\,B'_j(\boldsymbol{x},t)\right\rangle\cdot \tag{14}$$

To illustrate the effects of turbulent magnetic fields on solar oscillations, we suppose the magnetic effect dominates over other effects, i.e., the force $\boldsymbol{f}(\boldsymbol{u})$ is negligible. However, in the absence of an unperturbed velocity field, if we consider the problem of incompressible, homogenous, isotropic MHD turbulence with no mean magnetic field, Eq. (12) is reduced to

$$\frac{\partial \boldsymbol{v}'}{\partial t} = -\frac{1}{\rho_0}\nabla P' - \nabla\Phi' - \frac{\rho'}{4\pi\rho_0^2}\nabla\cdot\mathfrak{B}. \tag{15}$$

2.2. Dispersion relation for sound waves in a fluctuating magnetic field

As the simplest possible equilibrium situation, we consider the spatially homogeneous and time-independent case, where all derivatives of equilibrium quantities vanish. Such a situation clearly cannot be realized in practise. However, if the equilibrium structure varies slowly relative to the oscillations, this may be a reasonable approximations. In addition, the perturbation in the gravitational potential can be neglected (Christensen-Dalsgaard 1998; 2002). By taking the divergence, the equation of motion (15) approximately gives

$$\frac{\partial}{\partial t}(\nabla\cdot\boldsymbol{v}') = -\frac{1}{\rho_0}\nabla^2 P' - \frac{1}{4\pi\rho_0^2}\nabla\cdot(\rho'\nabla\cdot\mathfrak{B}). \tag{16}$$

However, $\nabla\cdot\boldsymbol{v}'$ can be eliminated by using the continuity Eq. (11), and P' can be expressed in terms of ρ' from the adiabatic approximation, which is given by

$$P' = c_0^2\rho', \tag{17}$$

where the adiabatic sound speed is given by

$$c_0^2 \equiv \frac{\Gamma_1 P_0}{\rho_0}, \tag{18}$$

with the adiabatic exponents

$$\Gamma_1 = \left(\frac{\partial\ln P_0}{\partial\ln\rho_0}\right)_{\rm ad}.$$

Then, Eq. (16) can be written as

$$\frac{\partial^2\rho'}{\partial t^2} = c_0^2\nabla^2\rho' + \frac{1}{4\pi\rho_0}\nabla\cdot(\rho'\nabla\cdot\mathfrak{B}). \tag{19}$$

If the oscillations are regarded locally as plane waves, a perturbation in the density has the form of plane waves, i.e.,

$$\rho' = a \exp\left[i\left(\boldsymbol{k}\cdot\boldsymbol{r} - \omega t\right)\right], \tag{20}$$

where the local wavenumber $\boldsymbol{k}$ can be separated into radial and horizontal components as

$$\boldsymbol{k} = k_{\rm r}\boldsymbol{a}_{\rm r} + \boldsymbol{k}_{\rm h}, \tag{21}$$

with

$$k_{\rm h}^2 = \frac{L}{r^2},$$

here $\boldsymbol{a}_{\mathbf{r}}$ is a unit vector in the radial direction, and $L^2 = \ell\,(\ell+1)$.

By substituting Eqs. (20) into (19), the dispersion relation can be obtained

$$\omega^2 = c_0^2\,|\boldsymbol{k}|^2 - \frac{i}{4\pi\rho}\boldsymbol{k}\cdot(\nabla\cdot\boldsymbol{ß}) - \frac{1}{4\pi\rho_0}\nabla^2\cdot\boldsymbol{ß}, \tag{22}$$

which is the form of an eigenvalue problem, ω^2 being the eigenvalue. Clearly, Eq. (22) shows that the properties of p-modes are not only controlled by the variation of the adiabatic sound speed $c_0(r)$, but also modified by the turbulent magnetic fields.

2.3. The effect of turbulent magnetic fields on damping of acoustic modes

Near the surface, the ratio of the horizontal and radial displacements is given by (Bi & Li 1998)

$$\frac{\xi_{\rm h}}{\xi_{\rm r}} \approx \frac{\ell g}{\omega^2 R} \approx 10^{-3}\ell\left(\frac{3\ {\rm mHz}}{\nu}\right)^2, \tag{23}$$

where $\omega = 2\pi\nu$. If $\ell < 10^3$, then the oscillations of a typical frequency of 3 mHz are almost radial near the surface. Therefore, for low-ℓ p-modes, we can restrict ourselves to radial oscillations.

To describe the radial variation of the mode, by making use of Eq. (22), the radial wave number $k_{\rm r}$ is approximately given by (Christensen-Dalsgaard 1998)

$$\begin{aligned} Re\,(k_{\rm r}) &\approx \frac{\omega}{c_0}\left[1 - \frac{L^2c_0^2}{\omega^2r^2} + \frac{1}{4\pi\rho_0\omega^2r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial ß_{rr}}{\partial r}\right)\right]^{1/2} \\ &\simeq \frac{\omega}{c_0}\left[\left(1 - \frac{L^2c_0^2}{\omega^2r^2}\right)^{1/2}\right. \\ &\quad \left. +\frac{1}{8\pi\rho_0\omega^2r^2}\left(1 - \frac{L^2c_0^2}{\omega^2r^2}\right)^{-1/2}\frac{\partial}{\partial r}\left(r^2\frac{\partial ß_{rr}}{\partial r}\right)\right], \end{aligned} \tag{24}$$

where in the last equality we assume that the influence of the magnetic field is small. The requirement of a standing wave in the radial direction implies that the integral of k_r over the region of propagation must be an integral multiple of π, that is (Unno et al. 1989)

$$\int_{r_t}^{R} Re\,(k_{\rm r})\,{\rm d}r = n\pi, \tag{25}$$

where R and $r_{\rm t}$ are the radii at the surface and the inner turning point, respectively. The inner turning point is determined by

$$\frac{c_0^2\,(r_{\rm t})}{r_{\rm t}^2} = \frac{\omega^2}{\ell\,(\ell+1)}. \tag{26}$$

By substituting Eqs. (24) into (25), we obtain

$$\begin{aligned} \frac{n\pi}{\omega} &\simeq \int_{r_{\rm t}}^{R}\left(1 - \frac{L^2c_0^2}{\omega^2r^2}\right)^{1/2}\frac{{\rm d}r}{c_0} \\ &\quad +\frac{1}{8\pi\omega^2}\int_{r_{\rm t}}^{R}\left(1 - \frac{L^2c_0^2}{\omega^2r^2}\right)^{-1/2}\frac{1}{\rho_0r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial ß_{rr}}{\partial r}\right)\frac{{\rm d}r}{c_0}. \end{aligned} \tag{27}$$

It is well known that most of the modes observed in the Sun are essentially acoustic modes, and the frequencies of solar oscillation satisfy the simple functional relation known as the Duvall law (Duvall 1982). If the second term of the right-hand side of of Eq. (27) can be neglected, we obviously obtain the usual Duvall law. Hence, Eq. (27) clearly shows the modifications by turbulent magnetic fields to the properties of acoustic modes.

We express the frequency in terms of real and imaginary parts as $\omega = \omega_{\rm r} + {\rm i}\omega_{\rm m}$, where $\omega_{\rm r}$ and $\omega_{\rm m}$ are the real and imaginary parts of the eigenfrequency, and assume that the contribution of fluctuating magnetic fields to frequency, $\omega_{\rm m}$, is weak, so that $Re\,(\omega) \gg Im\,(\omega)$. If we assume that the result changes the frequency from $\omega_{\rm r}$ to $\omega_{\rm r} + {\rm i}\omega_{\rm m}$, by multiplying Eq. (27) by $\omega_{\rm r}$ and perturbing it, we obtain

$$S\,\frac{\omega_{\rm m}}{\omega_{\rm r}} \simeq -\frac{1}{8\pi\omega_{\rm r}^2}\int_{r_{\rm t}}^{R}K\,(r)\,\frac{1}{\rho_0r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial ß_{rr}}{\partial r}\right){\rm d}r, \tag{28}$$

with

$$K\,(r) = \frac{1}{c_0}\left(1 - \frac{L^2c_0^2}{\omega_{\rm r}^2r^2}\right)^{-1/2}, \tag{29}$$

and

$$S = \int_{r_t}^{R}\left(1 - \frac{L^2c_0^2}{\omega_{\rm r}^2r^2}\right)^{-1/2}\frac{{\rm d}r}{c_0}. \tag{30}$$

If we use the asymptotic behavior of the eigenfunctions, Eq. (28) can be written as

$$\frac{\omega_{\rm m}}{\omega_{\rm r}} \simeq -\frac{1}{8\pi\omega_{\rm r}^2 I}\int_{r_{\rm t}}^{R}K\,(r)\,\frac{1}{\rho_0r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial ß_{rr}}{\partial r}\right){\rm d}r, \tag{31}$$

where

$$I = \int_0^R \rho_0r^2\left[\xi_{\rm r}\,(r) + \ell\,(\ell+1)\,\xi_{\rm h}^2\,(r)\right]{\rm d}r. \tag{32}$$

It can be clearly seen from Eq. (31) that the question of stability or instability depends on the sign of $\frac{\partial}{\partial r}\left(r^2\frac{\partial ß_{rr}}{\partial r}\right)$: if $\frac{\partial}{\partial r}\left(r^2\frac{\partial ß_{rr}}{\partial r}\right) < o$ the mode is unstable, whereas if $\frac{\partial}{\partial r}\left(r^2\frac{\partial ß_{rr}}{\partial r}\right) > 0$ the mode is stable, e.g., the fluctuating magnetic field gives a negative contribution to $\frac{\omega_{\rm m}}{\omega_{\rm r}}$, and hence contributes to the damping of modes.

3. The spectrum of fluctuating magnetic fields

For a stationary convective turbulence, we can use a simple assumption about a random flow $\boldsymbol{u}$ to generate a fluctuating magnetic field $\boldsymbol{B}'$ with the same probability as $-\boldsymbol{B}'$, and therefore the pattern of magnetic perturbations can be described in the same way as the case of turbulent velocities as the true Navier-stokes field (Boldyrev & Cattaneo 2004). The second-order correlation product of fluctuating magnetic fields is written as

$$\mathfrak{B}_{ij} = H_{ij}(\boldsymbol{x} - \boldsymbol{x}')\chi(t - \tau), \tag{33}$$

where $\tau \simeq \ell/\upsilon$ is the correlation time of the turbulence, and $\ell = \alpha H_{\rm p}$ is the corresponding correlation length of the magnetic field fluctuations, with mixing-length constant α and vertical pressure scale $H_{\rm p}$, which is the dominant local length scale in the convection zone.

As the simplest case, the temporal part of the magnetic spectrum, which could be suitable for connecting the variation of turbulent magnetic field with the activity cycle, is estimated from Bi et al. (2003)

$$\chi(t-\tau) = \frac{1 - \lambda\cos\left[2\omega_{\rm cyc}(t-\tau)\right]}{1-\lambda}, \tag{34}$$

where λ is a factor that describes the characteristic of temporal behavior in the magnetic energy spectrum. We consider that the factor λ varies with depth and time, but here it is treated as a constant for simplicity. $\omega_{\rm cyc}$ is the frequency of the solar magnetic cycle, i.e., $\omega_{\rm cyc} = 2\pi/T_{\rm cyc}$, $T_{\rm cyc} = 22$ yr, and the time lag τ takes into account a smoothing effect for the time spectrum.

Assuming that the fluctuating magnetic field is incompressible, homogeneous and isotropic, the magnetic correlation function has the form

$$H_{ij}(r) = h(r)\left(\delta_{ij} - \frac{r_i r_j}{r^2}\right), \tag{35}$$

where $r = \boldsymbol{x} - \boldsymbol{x}'$.

If we further assume energy equipartition for the local spectra, as Kichatinov (1991)

$$\frac{\rho_0}{2}h(k) = \frac{1}{8\pi}u(k), \tag{36}$$

where $h(k)$ and $u(k)$ are the Fourier transform of the fluctuating magnetic spectrum and the turbulent velocity spectrum, respectively.

We set the spectrum of the kinetic energy of MHD turbulence close to Kolmogorov's one

$$u(k) = a\frac{u_0^2}{k_0}\left(\frac{k}{k_0}\right)^{-5/3}, \tag{37}$$

where u_0^2 is proportional to the mean square turbulent velocity, $k_0 \simeq 2\pi/H_{\rm p}$ represents the characteristic scale of energy-containing eddies. The factor $a = 0.758$ is determined by the normalization condition.

Therefore, by using Eq. (37), we obtain the spatial spectrum of the magnetic fluctuations (Kleeorin et al. 1996)

$$h(k) = \frac{8}{9}\frac{\delta B_0^2}{k_0}\left(\frac{k}{k_0}\right)^{-1}, \tag{38}$$

where δB_0 is proportional to the mean strength of the fluctuating magnetic fields. It represents the magnitude of magnetic energy.

Following Bi et al. (2000), for low-ℓ p-modes we only consider the contribution of the radial part of the relation tensor to the damping. Then, the spatial component of magnetic energy spectrum is

$$H_{rr}(r) = 2\int_0^\infty h(k)\left(\frac{\sin kr}{k^3r^3} - \frac{\cos kr}{k^2r^2}\right)\mathrm{d}k. \tag{39}$$

4. Results of linearized stability computations

In this paper, we only consider the influence of MHD turbulence on solar damping by neglecting the contribution of fluctuating magnetic fields to the hydrostatic support. It is interesting to examine the effects of magnetic fields on solar damping with a simple model of time-dependent MHD turbulence. Our work is divided into steps. The first is to investigate the effects of the temporal component of the magnetic spectrum; the second is to test the influence of the magnitude of magnetic energy on the damping by using various values of δB_0.

4.1. Temporal behavior in the stability

This section describes the effects of temporal changes of fluctuating magnetic fields on the damping rates for solar low-ℓ p-modes. We note that the factor λ in Eq. (34) is related to the MHD turbulent properties. In order to match the solar-cycle variations in the damping rates, if the contribution of turbulent magnetic fields to the damping is significant, λ must lie between 0 and 1. For simplicity, we set factor $\lambda = 0.6$ here.

For $\ell = 0$, $\delta B_0 = 50$ G, and frequency of the order of 3 mHz in the integral of Eq. (31), the damping rate is a function of time, which can be seen from Eq. (33). For the adiabatic equilibrium model, an example of the stability coefficient $\eta_{\rm m} \equiv -\frac{\omega_{\rm m}}{\omega_{\rm r}}$ over a solar cycle is plotted in Fig. 1. The stability coefficient is defined in such a way that negative values imply instability.

Figure 1 clearly shows that the stability coefficients are sensitive to the synthetic temporal changes of fluctuating magnetic fields, roughly consistent with the observed behavior of the solar cycle (Komm et al. 2000a; Gelly et al. 2002; Howe et al. 2003). Although the time variation of damping analyzed here is based on a simple model of time-dependent MHD turbulence, the obtained variation of linewidth with time shows a significant correlation with the solar cycle.

If the variations of measured linewidth with the solar cycle are indeed the result of changes in fluctuating magnetic fields of the solar convective zone, this raises the possibility of long-term changes in solar structure associated with magnetic fields, thus providing information about the physical nature of the magnetic activity.

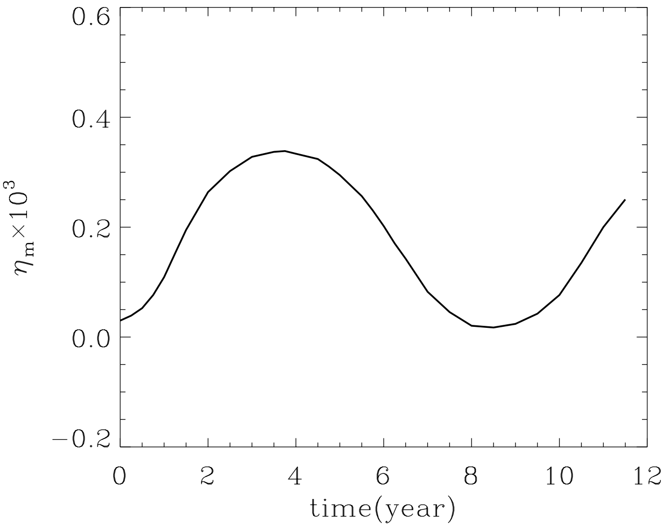

Fig. 1. Time variation of stability coefficient, η_m, for modes with $\ell = 0$ and $\delta B_0 = 50G$ over a complete solar cycle.

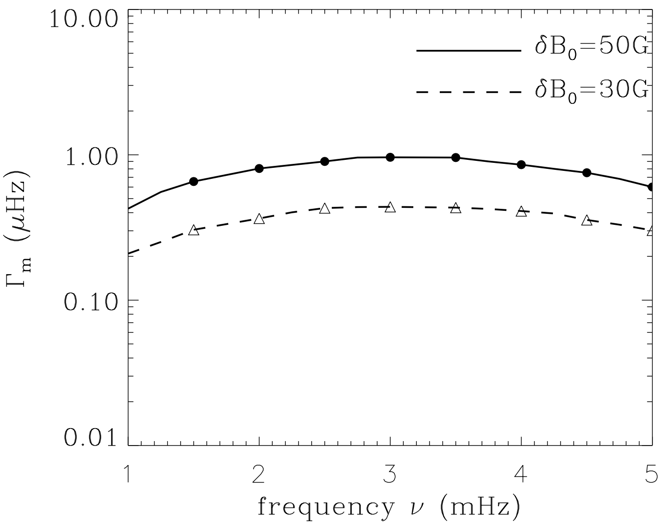

Fig. 2. Line widths as a function of cyclic frequency, $\nu = \omega_r/2\pi$, for the synthetic MHD turbulent spectrum. The solid line joined by circles and the dashed line joined triangles refer to the calculations of δB_0 = 50 G and δB_0 = 30 G, respectively.

4.2. Sensitivity of the damping to the magnetic strength

According to our model of time-dependent MHD turbulence, the magnitude of solar damping over the cycle is not only related the temporal component, but depends strongly on the spatial component of the magnetic spectrum. Here, the main aim is to check the dependence of damping on the magnitude of magnetic energy. We set $\lambda = 0.6$.

If we set $t = 0$, the theoretical linewidth $\Gamma_m = -\omega_m/\pi$ mainly depends on the spatial component of the magnetic spectrum. As a test of this statement, the calculations of linewidths are performed for different choice of the spatial magnetic energy spectrum, e.g. corresponding to the various mean strength of fluctuating magnetic fields, δB_0, which represent the magnitude of magnetic energy. The numerical results of the theoretical linewidths with $\ell = 0$ modes are presented in Fig. 2 for different values of δB_0. Figure 2 clearly shows that the magnitude of the damping rate depends mainly on the choice of the magnetic energy spectrum. It is evident that the larger the magnetic field, the larger the damping. Therefore, it means that there is more p-mode damping at high-activity than at low activity.

It can be seen from Fig. 2 that there is no obvious difference between lower and higher frequencies for the linewidths. The effects of turbulent magnetic fields on the damping become greater toward lower and middle frequencies in the range below 4 mHz. This might be explained by the contribution of magnetic viscosity or by anisotropic properties in the real situation, which might be neglected by us for simplicity.

By suitably adjusting the MHD turbulence parameter, the theoretical linewidth obtained at δB_0 = 50 G, about 1 μHz near 3 mHz, is in reasonable agreement with observed p-mode linewidths (Gelly et al. 2002). This clearly indicates that the turbulent magnetic field indeed contributes to the damping of solar p-modes, and solar low-ℓ p-modes are likely stable, one of the dominant stabilizing effects being the turbulent magnetic fields. Therefore, we would like to investigate the possibility of inferring the strength of fluctuating magnetic fields in the solar interior by helioseismology.

From the comparison between the above figures and the observational data for the damping of low-ℓ solar p-modes, a significant turbulent magnetic field may be present, that brings a new property to the structure of convection zone. However, we can not fit our calculations to observations, especially in higher frequencies range, since the values of the damping closely depends on the distribution of turbulent magnetic fields, which is more complicated in the real case.

Nevertheless, our results provide a physical explanation for the observed variation of damping of low-ℓ p-mode over the solar cycle, caused by the contribution of turbulent magnetic fields. Moreover, it is clear that the detailed measurement of the linewidths of the solar p-modes may provide useful constraints on the properties of near-surface convection, which dominates the excitation and damping of the modes.

5. Conclusions

In this paper we investigate the influence of the change in the temporal and spatial distribution of the magnetic energy spectrum on the damping We have seen that the presence of a fluctuating magnetic field adds a new element to the structure of the convection zone and properties of oscillations.

1. A background isotropic MHD acts as a linear damping mechanism for solar p-mode oscillations. The damping process of solar oscillations, by using a simple model of time-dependent MHD turbulence, can be expressed as the stability equation. The stability depends mainly on the structure of the turbulent magnetic fields.
2. Attempts have been made to identify the presence of turbulent magnetic fields that can cause the changes the measured damping during the solar cycle. Time-dependent

MHD turbulence has direct effect on the damping of solar p-modes.

3. The damping of low-ℓ p-modes are sensitive to solar magnetic activity, revealing possible structural changes deep inside the convection zone as the solar cycle progresses.

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