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Nonadiabatic p-mode pulsations of magnetic stars

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Abstract. Properties of nonadiabatic axisymmetric nonradial pulsations of magnetic stars are discussed. Frequencies and the amplitude modulations of the roAp star HR1217 are compared with theoretical ones.

Key words. Stars: magnetic fields – Stars: oscillations – Stars: variables

1. Introduction

Rapidly oscillating Ap (roAp) stars were discovered by Kurtz (1982). They are located in the δ Scuti instability strip (dashed lines in Fig.1) on the HR diagram. They show short periods (5 – 15 min) variations rather than long-period (δ Scuti-type) ones. Those variations are caused by low-degree high-order p-mode pulsations modified by strong magnetic fields. The frequency of a pulsation mode is shifted in the presence of a strong magnetic field, and the pulsation is damped by the generation of magnetic slow waves (Roberts & Soward 1983).

The effects of magnetic fields on nonradial pulsations have been investigated using adiabatic approximation by Dziembowski & Goode (1996); Cunha & Gough (2000); Bigot et al. (2000); Saio & Gautschy (2004). Recently, Saio (2005) extended Saio & Gautschy (2004)'s analysis to nonadiabatic pulsations.

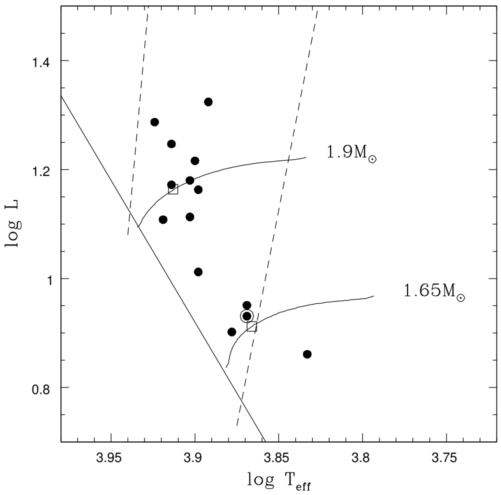

Fig. 1. Some of the roAp stars (black dots; encircled one for HR 1217) are plotted on the HR diagram with evolutionary tracks of $1.9M_\odot$ and $1.65M_\odot$. Open square on the $1.9M_\odot$ track is the model adopted in Saio (2005) and the one on the $1.65M_\odot$ track is the model adopted for HR1217 in this paper.

2. Nonadiabatic pulsation

In the presence of a magnetic field, the angular dependence of a nonradial pulsation cannot be represented by a single spherical harmonic

Y_ℓ^m. We expand the eigenfunction into a truncated series of terms proportional to spherical harmonics. To make the problem simpler, we neglect rotation, and assume the unperturbed magnetic field to be dipole. Furthermore, we consider only axisymmetric modes ($m = 0$), for which no toroidal displacement need to be considered. Then, the displacement vector $\boldsymbol{\xi}$ can be expressed as

$$\boldsymbol{\xi} = \sum_\ell \left[\boldsymbol{e}_r \xi_r^\ell(r) + \boldsymbol{e}_\theta \xi_h^\ell(r) \frac{d}{d\theta} \right] Y_\ell^0,$$

where $\ell = 1, 3, 5 \ldots$ for odd modes, $\ell = 0, 2, 4, \ldots$ for even modes. To identify the type of a mode we use ℓ_m which refers to ℓ of the component having the largest kinetic energy.

Saio (2005) discussed nonadiabatic pulsations of a $1.9 M_\odot$ main-sequence model (Fig.1). In this model, low-frequency ($0.3 \sim 0.6$mHz) p-modes and high-frequency ($1.8 \sim 2.6$mHz) p-modes are excited in the absence of a magnetic field. The latter are excited by the κ-mechanism in the H-ionization zone, while the former are excited by the κ-mechanism in the He II ionization zone.

All the low-frequency modes are found to be stabilized in the presence of a magnetic field stronger than $B_p \sim 1$kG, where B_p is the magnetic field strength at poles on the stellar surface. This is consistent with the fact that no δ Scuti type low-order pulsation is observed in roAp stars.

On the other hand, for excited high-frequency p-modes, $\ell_m = 1, 2, 3$ modes remain overstable even in the presence of a strong magnetic fields. It is found, however, that high-order quasi-radial modes are stabilized by the effect of the magnetic field. This result suggests that distorted dipole modes and distorted quadrupole modes are most likely excited in roAp stars. It should be noted, however, that the stability of high-order p-modes depends considerably on the assumptions made for optically thin layers and the location of the outer boundary.

3. A preliminary model for HR1217

HR 1217 (=HD 24712) is one of the best studied roAp stars. Most recently, Kurtz et al. (2005) obtained eight frequencies (plus rotational sidelobes) ranging from 2.62mHz to 2.81mHz (see Fig.2 left panel). The position of HR 1217 on the HR diagram is shown by an encircled black dot in Fig.1 close to the evolutionary track of $1.65 M_\odot$. We have adopted a model of $(M, \log L, \log T_{\rm eff}) = (1.65, 0.912, 3.866)$ for HR 1217, in which we have assumed convection to be suppressed by a magnetic field.

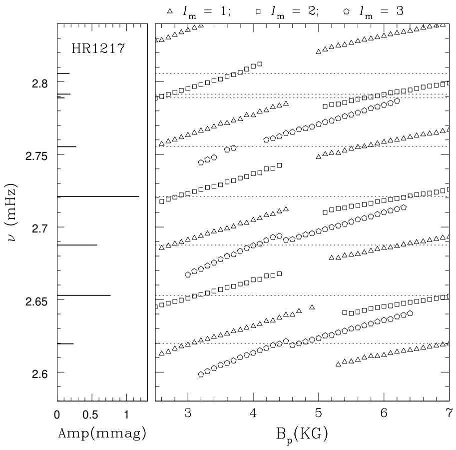

Fig. 2. The left panel shows frequencies and amplitudes of HR 1217 obtained by Kurtz et al. (2005) for the 2000 data. The right panel shows theoretical pulsation frequencies of $\ell_m = 1, 2, 3$ modes as a function of the strength of magnetic fields for the model of $1.65 M_\odot$ whose location on the HR diagram is shown in Fig.1.

3.1. Pulsation frequencies and stability

The large frequency separation of our model is, in the absence of a magnetic field, about 71μHz, which is close to the observed value 68μHz (e.g. Kurtz et al. 2005). Some low-order modes with periods of ~ 2 hour – 30 minutes are excited in the absence of a magnetic field. Those modes are stabilized when $B_p \gtrsim 1$kG. (We note, however, that for modes with periods longer than about 1 hour the accuracy of our method was not enough to determine the stability in the presence of a magnetic field.)

The left panel of Fig.2 shows observed amplitudes and frequencies of HR 1217 (rotational sidelobes are not shown). The right panel shows calculated pulsation frequencies for $1 \leq \ell_m \leq 3$. Each sequence is terminated when ℓ_m shifts to higher than 3, or when the convergence of the expansion becomes poor. For the model all of those high-order modes are, unfortunately, damped. The stability of the high-order modes is sensitive to the structure and assumptions in radiative transport in the optically thin layers.

The three largest-amplitude frequencies (2.721 mHz, 2.687 mHz, 2.653 mHz) of HR 1217 are reasonably reproduced by two $\ell_m = 2$ modes and one $\ell_m = 1$ mode at $B_p \approx 3$kG or at $B_p \approx 6$kG (Fig.2). Fig.3 shows damping rates (bottom panel) and frequencies (top panel) for two of those modes as a function of B_p. The damping rates of these modes are small at $B_p \sim 3$kG and $\sim 6 - 7$kG, for which they are likely excited if the κ-mechanism driving is strong enough. This is consistent with the fact that at these values of B_p theoretical frequencies are similar to the observed ones. However, the theoretically preferred ranges of B_p are not consistent with the observational estimates of the magnetic field of HR 1217; Bagnulo et al. (1995) obtained $B_p = 3.9$ kG, and Ryabchikova et al. (1997) obtained 4.4 kG.

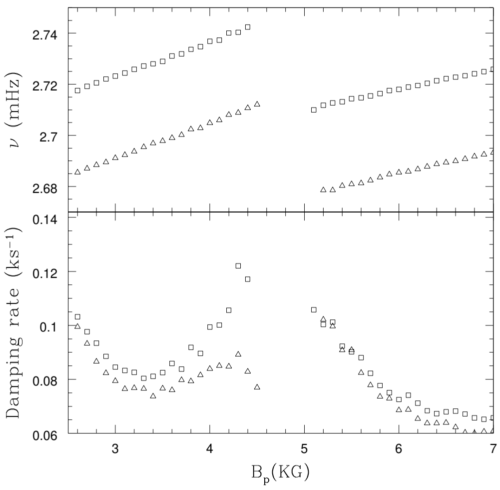

Fig. 3. Nonadiabatic pulsation frequencies (upper panel) and damping rates (lower panel) of selected high-order modes of $\ell_m = 1$ (triangles) and $\ell_m = 2$ (squares), which have frequencies similar to those observed high-amplitude modes. Wiggles in damping rates are from the limitation in the numerical accuracy. Between $\sim$ 5 kG and $\sim$ 4.6 kG, the magnetic-acoustic coupling are too strong for the expansion of the eigenfunction to converge.

3.2. Amplitude modulation

HR 1217 rotates with a period of 12.457 days (Kurtz et al. 2005). Since the direction of the pulsation axis changes with rotation, pulsation amplitude modulates with the rotation phase. This amplitude modulation causes rotational sidelobes, whose amplitudes depend on the shape of the modulation curve which in turn depends on the latitudinal dependence of the pulsation amplitude, inclination (i) of the rotation axis to the line of sight, and the angle (β) between the rotational and magnetic axis. Figs.4 and 5 show predicted amplitude modulations and the corresponding amplitude spectra for the 2.72 mHz $\ell_m = 2$ and 2.69 mHz $\ell_m = 1$ mode at $B_p = 6$kG, where a magnetic obliquity of $\beta = 150°$ and a rotational inclination of $i = 137°$ are adopted (or equivalently, $\beta = 40°$ and $i = 43°$) according to the estimate by Bagnulo et al. (1995).

One of the convenient parameters to discuss the amplitude modulation is $\gamma^+ = (A_+ + A_-)/A_0$, where A_+ and A_- are the amplitudes of the higher- and lower-frequency rotational sidelobes, respectively, and A_0 is the amplitude of the central frequency. Since the rotational effect on the eigenfunction is neglected in our analysis, the sidelobes shown in Figs 4 and 5 are symmetric;i.e., $A_+ = A_-$ (cf. Bigot & Dziembowski 2002). Our model predicts $\gamma^+ =$ 0.64, 0.61 and 0.68 for the 2.72 mHz ($\ell_m = 2$), 2.69 mHz ($\ell_m = 1$) and 2.65 mHz ($\ell_m = 2$ not shown) mode at $B_p = 6$kG, respectively. On the other hand, Kurtz et al. (2005) obtained 0.67, 0.84, and 0.59 from the 2000 data (0.52, 0.82, and 0.68 from the 1986 data), respectively. The predicted γ^+ for the 2.69 mHz mode is somewhat smaller than the observed values, and for the other two modes predicted values marginally agree with the observed values.

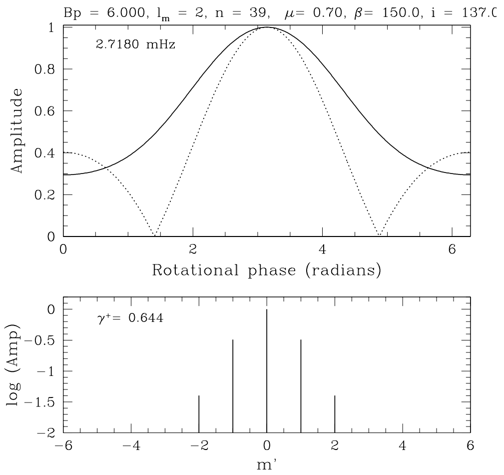

Fig. 4. A predicted amplitude modulation with the rotation phase (top panel) and relative amplitudes of rotationally splitted components (bottom panel) for 2.72 mHz $\ell_m = 2$ mode at $B_p = 6$kG, where magnetic and rotational inclinations of $\beta = 150°$ and $i = 137°$ are assumed. Dotted line in the top panel shows the amplitude modulation expected when the latitudinal amplitude dependence is given by the Legendre function $P_2(\cos\theta)$.

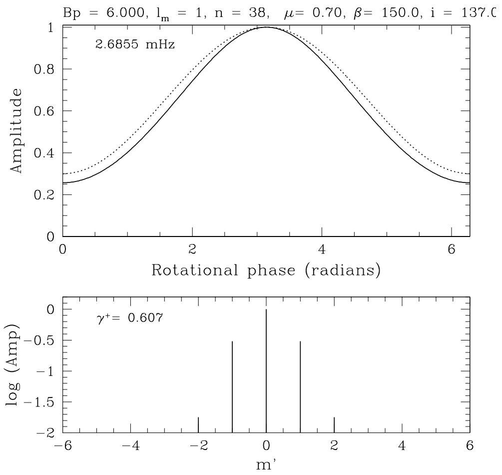

Fig. 5. The same as Fig.4 but for 2.69 mHz $\ell_m = 1$ mode. Dotted line in the top panel shows the amplitude modulation expected when the latitudinal amplitude dependence is given by the Legendre function $P_1(\cos\theta)$.

4. Conclusion

We discussed the properties of nonadiabatic pulsations in the presence of a dipole magnetic field. The low-order modes are stabilized in the presence of a few kG due to a leakage of pulsation energy by slow waves. High order modes, on the other hand, can be remained unstable in the presence of a strong magnetic field if the kappa-mechanism driving in the H-ionization zone is strong enough. Our stability analysis suggests that all quasi-radial modes are damped, and deformed dipole and quadrupole modes are most likely excited in roAp stars.

Frequencies and the amplitude modulations of the roAp star HR1217 were compared with theoretical ones. Although calculated frequencies are more or less consistent with the observed frequencies, our model fails to excite those pulsations. The stability and detailed properties of pulsation models depend on the assumptions adopted in optically thin layers. It is necessary to improve the treatment of the outermost layers in the nonadiabatic analysis.

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