HELIUM DIFFUSION IN RAPIDLY OSCILLATING Ap STARS

N. Dolez, D. O. Gough, S. Vauclair
Observatoires du Pic-du-Midi et de Toulouse, France
Institute of Astronomy and Department of Applied Mathematics and Theoretical Physics, University of Cambridge, UK

ABSTRACT. Suppression of convection near the poles of magnetic A stars and inhibition of winds near the equator influence chemical composition gradients resulting from diffusion, leading to appreciable horizontal variation in the equilibrium configurations of the stars. We conjecture that it is this variation which is responsible for the apparent alignment of non-radial pulsations with the magnetic axes of the stars, and also for a possible previous misidentification of the modes. We suggest that nonadiabatic excitation can be sufficient to overcome energy leakage into the atmosphere.

1. INTRODUCTION

The importance of diffusion in magnetic stars was recognised by Dolez and Gough (1982) in an attempt to explain Kurtz's (1982) observations that non-radial oscillations are aligned with the magnetic field. Dolez and Gough presumed that as a result of magnetic inhibition of convection near the poles, diffusion is enhanced and helium is therefore depleted, whereas the helium abundance near the equator is normal. This led to aligned modes being preferentially damped, in apparent contradiction with the observations. Here we show that in the presence of a wind the helium abundance can actually be enhanced at the poles. Moreover, in the equatorial regions where the wind is suppressed, helium can be depleted by diffusion beneath the convection zones. Thus there is the possibility that aligned modes are preferentially excited. We have not yet demonstrated whether that is actually the case. Nevertheless, we do show that the lateral variation of the surface layers of the star causes axisymmetric oscillations to be aligned with the field.

2. DIFFUSION AND ADVECTION AT MAGNETIC POLES

Helium diffusion in a wind was invoked by Vauclair (1975) to account for helium-rich stars, and remains the only known explanation for them.

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These hotter main-sequence stars ($T_e \simeq 20000K$) are also magnetic (e.g. Borra, Landstreet and Mestel, 1982), and show helium superabundances by factors up to 3 at the magnetic poles. The explanation suggested by Vauclair is that ionized helium is advected upwards from the stellar interior by the wind, but in and immediately beneath the atmosphere, where helium is neutral and can diffuse downwards a hundred times faster, it is left behind to accumulate in the visible layers of the star.

The same process can occur in all magnetic stars, particularly Ap stars. The visible outcome can be different, however, because in cooler stars helium accumulates at greater depths. Moreover, this occurs for lower mass-loss rates. Our model of the poles is based on the assumption that convection is inhibited by the magnetic field, while the wind leaves freely. We find in a 1.6 $M_\odot$ model Ap star a helium accumulation around a depth of 0.1% of the stellar radius.

3. DIFFUSION AT THE MAGNETIC EQUATOR

We assume that near the magnetic equator the wind is suppressed by the horizontal field. The two convection zones are not inhibited, and overshooting (after Latour _et al_., 1976) maintains a uniform helium abundance to the base of the lower zone. We expect helium to diffuse freely beneath the lower zone: the magnetic field B reduces the diffusion velocity by a factor $(1 + \Omega_L^2 \; t_c^2)$, where Ω_L is the Larmor radius and t_c the collision time; $\Omega \; t_c \simeq 10^{-6}$ B at the base of the second convection zone, and we are not anticipating megagauss fields, particularly so near to the surface of the star. After about 10^7 years, once the helium abundance has been reduced by a factor 3, the helium convection zones disappear, leaving only the thin superficial hydrogen convection zone. There a magnetic field of only 10^4 G is sufficient to inhibit diffusion.

4. MATCHING POLE AND EQUATOR

We have built a model Ap star envelope consisting of a polar region at colatitudes less than α and a 'normal' equatorial region elsewhere, each computed according to the prescriptions described above and otherwise satisfying the usual equations of stellar structure. The equatorial region had a luminosity $L = 7.90 \; L_\odot$ and effective temperature $T_e = 8000K$; the poles had $L = 7.90L_\odot$ and $T_e = 8007K$, adjusted to render pressure and temperature continuous with the equatorial model at great depths.

5. ADIABATIC OSCILLATION EIGENFREQUENCIES

Because near the stellar surface low-degree p modes locally resemble radial modes, we have estimated cyclic non-radial oscillation eigenfrequencies ν_n of modes of order n and degree ℓ as appropriate

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averages $\nu_e + \Lambda_\ell(\nu_p - \nu_e)$ of the corresponding frequencies ν_e and ν_p of radial oscillations of spherically symmetrical stars with respectively the equatorial and polar structures of our model Ap star. In the frequency range 2mHz $< \nu_e <$ 3mHz, the frequency difference $\delta = \nu_p - \nu_e$ rises monotonically from 15μHz to 29μHz. We use these results to discuss two issues concerning HD24712 observed by Kurtz and Seeman (1983).

5.1 Mode identification

Shibahashi (1984) pointed out that the first five of the six almost uniformly spaced frequencies observed by Kurtz and Seeman are most likely associated with modes of alternately odd and even degree. From Kurtz's (1982) evidence of a triplet fine structure in two of the modes (labelled f_1 and f_2), Shibahashi suggested that these must have $\ell = 1$. Then, assuming that the slight nonuniformity in the separations is a product only of the structure of the core, as it is in the sun, he assigned $\ell = 0$, rather than 2, to the others ($f_3 - f_5$). The conclusion, which was upheld by Gabriel et al. (1985) and Shibahashi and Saio (1985), rests on the quantities $\Delta_1 \equiv (\nu_{n,0} - \nu_{n-1,1}) - (\nu_{n,1} - \nu_{n,0})$ and $\Delta_2 \equiv (\nu_{n,1} - \nu_{n-1,2}) - (\nu_{n-1,2} - \nu_{n-1,1})$ both being positive. However, Kurtz et al. (1985) found a modulation in the amplitudes of all the modes, and notwithstanding the frequency computations deduced that $f_3 - f_5$ were non-radial, with $\ell = 2$.

Our calculations for a 1.6 $M_\odot$ model show that for magnetic polar regions each occupying 10 - 15% of a hemisphere, the contributions $2(\Lambda_0 - \Lambda_1)\delta$ and $2(\Lambda_1 - \Lambda_2)\delta$ from the surface regions to Δ_1 and Δ_2 are somewhat greater in magnitude than the contributions from the core, but of opposite sign. Therefore the conclusion that $f_3 - f_5$ are quadrupolar can be reconciled with theory.

5.2 Alignment of oscillations with the magnetic axis

Since magnetic fields cannot prevent Coriolis precession of nonaxisymmetric modes relative to the star, Dolez and Gough (1982) proposed that individual modes are transient phenomena, being excited only when they happen to be aligned with the field. They implicitly assumed that the magnetic field was too weak to induce a significant rotation of the principal axes of the normal modes, and ignored the influence of the lateral inhomogeneity of the structure of the star on the orientation of the axes. Contrarily, Dziembowski and Goode (1985, 1986) argued that the magnetic field might actually be very intense, and that the axisymmetric modes are almost aligned with the poles by the direct action of the Lorentz force on both the oscillations and the hydrostatic balance of the unperturbed star. That requires megagauss fields (cf. Gough and Taylor 1984).

The lateral inhomogeneity in the outer layers of the star, produced indirectly as we have described by only kilogauss magnetic fields, influences oscillation eigenfunctions in a manner similar to direct magnetic field perturbations, and must therefore cause a significant rotation of the principal axes of the modes. Indeed, the condition that a principal axis is close to the magnetic axis is simply that the frequency perturbations Δ_ℓ are much greater in magnitude than

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the Coriolis precession frequency $C\Omega/2\pi$, where $\Omega/2\pi \simeq 0.93\,\mu$Hz is the cyclic rotation frequency of the star. According to the calculations of Shibahashi and Saio (1985), the Coriolis parameter C is about 3×10^{-3} for dipole modes with frequencies close to those observed by Kurtz and Seeman (1983), yielding $C\Omega/2\pi \simeq 3 \times 10^{-3}\,\mu$Hz. According to our calculations, Δ_ℓ is indeed much greater: it is typically several μHz, the precise value depending on n, ℓ and α. Therefore alignment of axisymmetric modes with the magnetic poles is an inevitable consequence of our model.

6. MODE EXCITATION AND THE ATMOSPHERIC TEMPERATURE

It remains to explain why it is the aligned axisymmetric modes that are preferentially excited, and why only modes in a narrow frequency range are observed. We have performed nonadiabatic calculations similar to those of Dolez and Gough (1982), and have found encouraging patterns in the growth rates. However, the growth rates depend quite sensitively on the details of our relatively crude treatment of radiative transfer in the atmosphere, and therefore we choose not to present the results here. The reason for the sensitivity is that the upper turning points of high-order p modes, when they exist, are close to the photosphere, and the structure of the eigenfunctions in the ionization zones where driving takes place is easily influenced by conditions in the atmosphere.

Subject to this uncertainty, we have found some modes that are unstable even when their frequencies exceed the adiabatic critical acoustic frequency in the atmosphere. For such modes, driving, which occurs principally in the He II ionization zone, exceeds the damping elsewhere and the energy loss from the surface. Therefore we must caution against concluding with Shibahashi and Saio (1985) that the temperature in the atmosphere of HD24712 is necessarily as low as 3200K.

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