THEORETICAL ASPECTS OF THE RAPIDLY OSCILLATING AP STARS

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1. What We Have Learned

Until the rapid oscillations in Przybylski's star, HD 101065, were discovered by Kurtz in 1978, chemical peculiarity and pulsation were thought to be mutually exclusive. Though the location of the Ap stars in the HR diagram overlaps with that of the Delta Scuti stars, no Ap stars were known to pulsate, and the Delta Scuti type pulsating stars, with a few exceptions, were not claimed to reveal chemical peculiarity. The striking impact of the discovery of the rapid oscillations of Ap stars is that the basic conception of the exclusiveness of the chemical peculiarity and the pulsation was broken. So far, twenty-nine Ap stars have been discovered to be rapidly oscillating Ap (roAp) stars (Kurtz 1997). The observed pulsations of Ap stars are, however, different from those of the Delta Scuti stars in various aspects. The pulsation periods of roAp stars are typically 10 minutes and are much shorter than those of the Delta Scuti stars, which are typically 2 hrs. In some cases, the amplitudes are modulated with the same period and phase as the magnetic strength variation. The amplitudes of some of the roAp stars are very stable, while some others show a fairly short-term variation of a time scale of a day. Some of the roAp stars show a long-term variation of the frequency with a time scale of years.

2. What We Have Succeeded in Explaining Pulsations of roAp Stars

For high order p-modes with low degree ($n \gg l \sim 1$), the eigenfrequency is asymptotically given by $\nu_{nl} \simeq (n + l/2 + 1/2)\nu_0$, where $\nu_0 \equiv (2\int_0^R c^{-1}dr)^{-1}$ is the reciprocal of the sound travel time from the stellar center to the stellar surface and back (Tassoul 1980). This asymptotic formula means that if a star is pulsating in many p-modes of low degree l, the observed spectrum is expected to show an almost equi-distant comb structure, in which frequencies with even and odd degrees with a separation of $\nu_0/2$, since unimaged measurements are sensitive only to modes with low degree. Many of the roAp stars show such equi-distant comb-like frequency spectra, and this feature is regarded as evidence that the observed luminosity variations are due to superposition of high overtone, low degree l acoustic eigenmodes of the star. From the comb-like structure, ν_0 can be determined. Comparison of the values of ν_0 thus obtained with theoretical values led to the conclusion that the evolutionary stage of roAp stars is the core hydrogen burning phase.

The frequency spectra of many roAp stars show triplet fine-structures with equal spacing. These fine-structures appear as a consequence of the fact the amplitudes are periodically modulated. From the fact that the amplitudes are modulated with the same period and phase as the magnetic field strength variation, it has been concluded that the oscillation modes are axisymmetric dipole modes whose symmetry axis coincides with the magnetic axis which is inclined to the rotation axis of the star (Kurtz 1982). The frequency separation of the fine structure is then regarded as the rotation frequency of the star. The relative amplitudes of the peaks of the fine structure depend upon the geometrical configuration of the star: the angle between the magnetic axis and the rotation axis, and that between the line of sight and the rotation axis. The amplitude pattern is not symmetric with respect to the central component of the fine structure. This asymmetry is caused by the effect of the Coriolis force (Dziembowski and Goode 1986, Kurtz and Shibahashi 1986). Detailed analyses of HR 3831 unveiled some low amplitude fine structure components and clarified that the fine structure, which used to be regarded as a triplet, is, in reality, a septuplet. Kurtz (1992) decomposed the

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fine structure into l = 0, 1, 2, and 3 components. Taking account of the perturbation of the eigenfunction due to the magnetic effect, Shibahashi and Takata (1993) and Takata and Shibahashi (1995) showed that the eigenfunction, which would be a pure dipole mode in the absence of the magnetic field, is deformed to have $l = 0$, 2, 3, and 4 components, and hence they justified Kurtz's treatment. Analyses of the amplitude pattern then provide us with the rotation period of the star, the geometrical configuration of the star, and the ratio between the effects of the Coriolis force and of the Lorentz force. The theoretical analyses outlined above are based on the regular perturbation method, in which the effect of the Lorentz force on the oscillations is treated as a small perturbation. It should be noted, however, that the magnetic and gas pressures are comparable in the photosphere, with the magnetic pressure dominating above the photosphere while it is negligibly small beneath the photosphere. Therefore, the regular perturbation method cannot be applied to the whole of a star. The transition occurs in a fairly thin layer, and hence treatment is difficult. Dziembowski and Goode (1996) criticized the application of the regular perturbation method, and devised a new method of treating the magnetic field. They argue that the observed modes depart significantly from normal modes and thus expect frequency multiplets with many components.

3. What Should Be Explained

We restrict our discussion only to the issues of the excitation mechanism of oscillations and the critical cut-off frequency, as the page length is limited.

Magnetic overstability was the first proposed possible excitation mechanism of the rapid oscillations of Ap stars (Shibahashi 1984). Even in the roAp stars, there must be a superadiabatic layer just beneath the photosphere, as in the normal A-type stars. In the case of magnetic Ap stars, magnetic tension makes the monotonic convective motion oscillatory, and the heat exchange associated with the oscillatory motion in the superadiabatic layer makes the amplitude of motion grow with time. This mechanism was, however, discussed only within the constraint of local treatment, and whether or not it works globally is still uncertain. The ordinary mechanism for the classical pulsating stars is the kappa mechanism. In the compression phase of pulsation, the radiative flux increases in the bulk of the star, since the temperature increase causes the material to become less opaque. However, in the partial ionization zone it is not the case, since the radiative flux from the stellar interior is blocked by the effect of the temperature dependence of opacity there. The blocked energy is converted to oscillation energy, and the oscillation amplitude grows with time gradually. For this mechanism to work properly, the partial ionization zone has to coincide with the transition region, where the total internal energy in stellar layers lying above the transition region is of the order of magnitude of the total energy radiated by the star in a pulsation period. In the case of the Delta Scuti type pulsating stars, the kappa mechanism due to He II ionization zone is responsible for pulsations. However, in the CP stars, helium is thought to be depleted in the layer corresponding to the He II ionization temperature. Hence the kappa mechanism due to He is not thought to be responsible for the rapid oscillations in Ap stars, and partial ionization of some other elements should be sought. Matthews (1988) considered the possibility of the kappa mechanism due to Si. Silicon is abundant in the atmosphere of some CP stars and the ionization potential of Si IV is close to that of He II, but slightly lower. So, if the kappa mechanism due to Si would excite stellar pulsations, the instability strip in the HR-diagram, due to this mechanism, should nearly overlap with the classical instability strip with a slight shift to lower temperature. This is plausible for explanation of the excitation mechanism of roAp stars. However, the total abundance of silicon is much less than helium, and then whether the kappa mechanism due to Si really works is suspect. Vauclair et al. (1991) considered the possibility of an accumulation of helium in a certain layer in the rapidly oscillating Ap stars, taking account of the effect of the stellar wind, and investigated the kappa mechanism due to He. Whether the roAp stars have really similarities to helium stars is, however, uncertain. Gautschy and Saio (1997) considered the kappa mechanism due to hydrogen. The hydrogen ionization zone is shallower than the He II ionization zone, and hence, for the kappa mechanism due to H to work, the transition region has also to be as shallow as the H ionization zone. The latter is satisfied only for short period oscillations. This is a plausible explanation of the rapid oscillations of Ap stars. Gautschy and Saio (1997) demonstrated that the high overtone p-modes can be excited by the kappa mechanism if a temperature inversion layer is assumed to exist. Why only a few high overtone radial order modes (only one in some cases) have

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large enough amplitudes to be detected is another issue to be explained. Although the pulsational stability is a delicate balance between radiative losses and the kappa mechanism, the eigenfunctions of high overtones look similar in the very outer layer. It is then expected that many eigenmodes having similar properties near to the photosphere can be excited to amplitudes of the same order of magnitude. The number of the detected oscillations is, however, only a few, contrary to the expectation. Why does the symmetry axis of the pulsations coincide with the magnetic axis of the star? A favorable condition for excitation by the kappa mechanism occurs when the eigenfunction has a larger amplitude in the ionization zone than elsewhere. This gives a general explanation why certain modes among many overtones with different radial order n are excited. The same might be true for the explanation for the reason why axial symmetric modes with respect to the magnetic axis are selectively excited. In the Ap stars, the distribution of the chemical elements may be almost axially symmetric with respect to the magnetic axis. If the chemical element responsible for the kappa mechanism, whatever it is, is accumulated in the magnetic polar region, the modes having large amplitudes in the polar region should be preferably excited. The axially symmetric modes have the largest amplitude at the magnetic poles, so they must be selectively excited. On the other hand, if the chemical elements responsible for the kappa mechanism are distributed mainly in the magnetic equatorial zone, the sectoral modes ($m = |l|$) having the largest amplitude at the equator must be selectively excited.

In the absence of the magnetic field, the acoustic waves can propagate in the atmosphere if the scale height is longer than the wavelength. Near to the photosphere, the scale height is very short so that acoustic waves from the stellar interior are reflected at a certain level, at which the scale height is equal to the wavelength of the oscillation. The waves having wavelength shorter than the shortest scale height in the atmosphere propagate further into the stellar corona, and the wave energy leaks from the system. Hence, it is unlikely that the star pulsates with frequencies higher than a certain cut-off frequency. However, some of the roAp stars are pulsating with very high frequencies, which are higher than the cut-off frequency of normal A-type stars. The cut-off frequency is dependent on the evolutionary stage of the star. For roAp stars, the evolutionary stage is well estimated from ν_0, and misidentification of the evolutionary stage is unlikely. The magnetic field decreases the cut-off frequency, and hence makes the apparent contradiction worse. The cut-off frequency is determined by the ratio between the sound speed and the scale height. Shibahashi and Saio (1985) proposed that the blanketing effect in the Ap stars' atmospheres would lead to a cool atmospheric layer which would be the cause of the high cut-off frequency atmosphere. Audard et al. (1997) recently constructed a model atmosphere of Ap stars with ATLAS9 and showed that the cut-off frequency of Ap stars is slightly higher than that of normal A-type stars. On the other hand, Gautschy and Saio (1997) consider the possibility of the existence of a temperature inversion layer, as in the case of the sun. If such a layer exists, the critical frequency is very high there, and it may explain the existence of very high frequency oscillations in Ap stars.

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