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KAPPA EFFECT PULSATIONAL INSTABILITY FOR HOT EXTREME HELIUM STARS

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ABSTRACT A long standing problem for the hydrogen deficient (extreme helium) stars has been the mechanism for the pulsation instability for the hottest members of this class. The usual κ mechanism works well for stars that are in the hydrogen and helium ionization instability strip, and this strip extends to perhaps 20,000K at high luminosity (Saio and Jeffery, 1988). However, several stars are definitely hotter. Investigations for another ionization instability strip, such as for carbon, have always shown that there is not enough carbon to produce a rapid enough increase of opacity with temperature to give the well-known κ effect. This is so even though these hydrogen deficient stars do show enhanced carbon in their spectra. A strong stellar wind can produce the observed hydrogen deficiency. Another popular mechanism is mass loss in a binary system through the Roche lobe. It now is possible that the missing pulsational instability mechanism is the rapid increase of iron lines absorption as the temperature increases above about 150,000K in the low density envelopes of these luminous stars. Recent calculations by Rozsnayi (1989) and Rogers and Iglesias (1989) at Livermore show that the n=3 to n=3 transitions in iron that were assumed unimportant in the earlier Los Alamos calculations (Cox, and Tabor 1976) can double or triple the opacity suddenly as the iron lines appear in a very sensitive part of the spectrum of the diffusing photons. It has been proposed that these iron lines also cause the many varieties of normal B star pulsations, and the hydrogen deficient stars are merely another example of this new κ effect for pulsating stars. The extreme helium star V2076 Oph at 31,900K, and 38,900 $L_\odot$ for a mass of 1.1 $M_\odot$ pulsates in the radial fundamental mode at about 1 day period with a very large linear growth rate when the iron lines more than double the opacity, but is stable otherwise. Probably the first one or two radial modes, but not the nonradial modes, are pulsationally unstable for many of the highly evolved hot stars by this mechanism.

BACKGROUND

Many of the luminous helium stars, such as the R CrB stars, the hydrogen deficient B stars and the extreme helium stars are observed to pulsate with periods from a fraction of a day to hundreds of days. Most of these stars are in the regular Cepheid instability strip, and their pulsations are driven by the usual κ and γ effects from helium ionization. This instability strip becomes much wider and its blue edge much bluer at high luminosity, at least for these low mass, highly evolved stars. The blue pulsating stars are driven at surface temperatures up to even 20,000K, probably because the κ effect opacity increase in these very low density envelopes occurs over a very small temperature range, giving a high enough logarithmic derivative of the opacity with respect to temperature. However, a few stars pulsate with surface temperatures even higher than this blue edge temperature. I investigate in this paper a possible pulsation mechanism for V2076 Oph with its effective temperature of 31,900K.

This star and others like BD +13°3224 at 28,000K, BD -9°4395 at 23,000K, and LSS 3184 at 22,000K may be pulsationally unstable by the sudden opacity increase due to iron lines at mass levels into the stars where the temperature is about 200,000K. This is again a κ effect, but unlike the normal effect, the opacity increase is not due to ionization. It is due to the increasing complexity of the iron atoms that have about half of their electrons ionized at 200,000K for the low densities of $5 \times 10^{-7}\ g/cm^3$. The bound valence electrons are in the M shell, and they can make numerous same-shell transitions that produce a tremendous opacity for the passing photons. A normal solar abundance of iron gives considerable κ effect pulsation driving.

The calculations that have produced these high opacities are from new Livermore programs and reported by Rozsnayi (1989) and Rogers and Iglesias (1989, 1990). These iron lines were missed in the Los Alamos opacity calculations, because these same-shell transitions are forbidden and have very small transition probabilities. It is the extremely large number of these transitions with overlapping line shapes that gives the interesting opacity increase.

It should be kept in mind that these pulsating extreme helium stars are frequently metal deficient, and maybe the iron lines do not give enough opacity increase to produce pulsations. Since the pulsating stars that we are discussing are very rare, it may be permissible to assume, however, that the solar iron abundance, unchanged by evolution, exists in them.

OPACITY DATA

The model for V2076 Oph discussed in this paper was generated in an unconventional way, because a complete opacity table including the newly discovered same-shell transition iron lines is not available. A guess for the opacity increase was made in the form of ramps that multiplied the opacity by varying factors for temperatures between 10^5 and 10^6K. Then temperature-density pairs in the model were given to Rogers and Iglesias at Livermore for detailed opacity calculations. Then a new set of ramps were coded in the model building program.

Table I gives the opacity factors relative to the opacity from the Los Alamos Astrophysical Opacity Library for the composition He9C1 that we now use for the low density giant extreme helium stars. Large opacity increases and large logarithmic derivatives with respect to temperature are found, but only in the narrow temperature range of 10^5 to 4×10^5K.

TABLE I Opacity Factors

$\rho\ (10^{-8} g/cm^3)$	$T\ (10^5 K)$	$\kappa_{LLNL}/\kappa_{LANL}$	$\kappa_{mod}/\kappa_{LANL}$
1.16	1.00	1.17	1.00
1.81	1.20	1.12	1.38
2.01	1.42	1.12	1.79
3.71	1.60	2.06	2.12
4.61	1.82	2.14	2.50
4.72	2.02	2.24	2.48
10.2	2.49	1.70	2.13
20.1	3.02	1.42	1.74
38.1	3.53	1.21	1.35
65.7	4.03	1.03	1.00
150.	5.01	0.94	1.00
299.	5.99	0.92	1.00
969.	7.98	1.00	1.00
2229.	10.03	0.99	1.00

V2076 OPH 1.1 SOLAR MASS MODEL

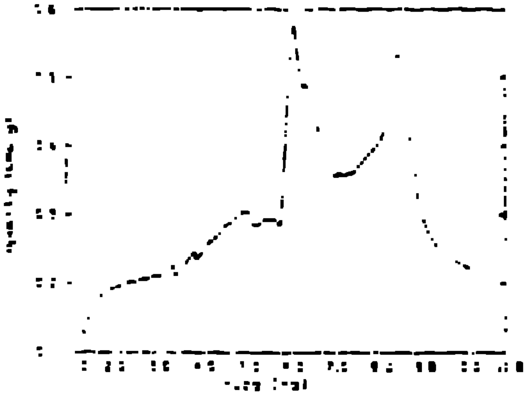
The model for this paper has a luminosity of 38,900 $L_\odot$, an effective temperature of 31,900 K, and an envelope composition of Y=0.96472, X_C=0.03516, and X_{Fe}=0.00012. For 1.1 $M_\odot$ this is almost at the Eddington limit luminosity. This 360 mass zone model then has a radius of 6.5 $R_\odot$. Less than 5 % of the stellar mass is in the model envelope which we extend down to 0.5 % of the radius. There are three convection zones in this model, but the only strong one between 10^{-7} and 10^{-6} of the mass into the model is where the pulsation driving is found. This convection zone extends from a temperature of about 90,000K to 300,000K between 0.840 and 0.326 of the model radius.

Figure 1 shows the opacity versus mass into the model. The important logarithmic derivative of the opacity with respect to temperature reaches between 1 and 2 at the important mass depth into the model, producing enough κ mechanism to overcome the otherwise strong damping in deeper levels. At more shallow depths there is the normal helium driving, where the logarithmic derivative of the opacity with respect to the temperature is even over 3, but at that depth, there is not enough mass involved to destabilize the entire model.

Figure 2 presents the work per zone versus the mass zone number. Two driving regions occur in the model, the outer one between zones 250 and 330 is the usual helium κ and γ effect destabilization. The additional, deeper driving is due to the iron line κ effect.

DISCUSSION AND CONCLUSIONS

The new iron line opacities from Livermore can explain the rare pulsations seen for very hot extreme helium stars. These opacities are also able to explain the model structure changes needed to decrease double-mode Cepheid period ratios to those observed (Andreasen, 1988). As reported by Cox (1990) and Cox and Morgan (1990), these increased opacities can also be used to predict the pulsations of the normal B stars, which are seen as β Cephei variables and related classes.



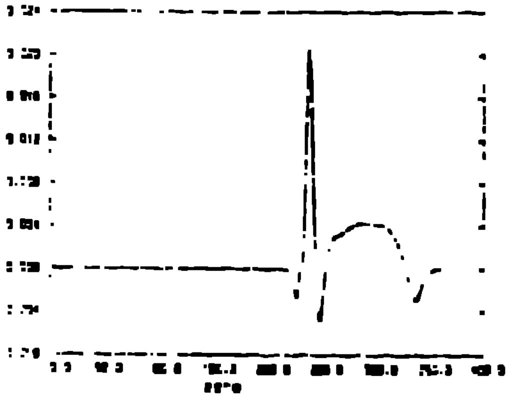


Fig. 1. Model opacity versus the external mass fraction.
Fig. 2. Work versus mass zone number showing two driving regions.

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