Modal Selection In Pulsating Stars

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MODAL SELECTION IN PULSATING STARS

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ABSTRACT

Initial-value and periodic nonlinear pulsation integrations are carried out for a series of double-mode Cepheid models ($P_1/P_0 \sim 0.7$) in the vicinity of the resonance $\omega_1 + \omega_0 = \omega_3$. None of the models tested shows persistent double-mode behavior. A new, semiquantitative description of modal selection, based upon the iterative theory of Simon, is introduced to analyze the nonlinear results. In the simplest version of this description, modal section categories emerge which are identical to those of Stellingwerf. Our hydrodynamic results also agree at least partially with Stellingwerf's in that we find a region in the red where the models approach (though never reach) simultaneous instability of both limit cycles. Analysis of resonant effects on modal selection in our calculations leads to the conclusion that models lying between the resonances $\omega_1 + \omega_0 = \omega_3$ and $P_2/P_0 = 0.5$ may yet be viable candidates for double-mode pulsation.

Subject headings: stars: Cepheids — stars: pulsations

I. INTRODUCTION

The theoretical study of finite-amplitude, instability-strip pulsations has been complex and difficult. While the list of factors (both physical and numerical) affecting the theoretical models is substantial, the large amount of computer time required for nonlinear calculations restricts extensive parameter variation. The resultant need to extract general principles from limited investigations has hindered progress. Among the many basic questions still unsolved in this area, perhaps the most important and least understood involves the phenomenon of modal selection.

It is by now well known that, over a considerable portion of the instability strip, models exist which are simultaneously unstable to infinitesimal perturbations in more than one normal mode—most importantly, in the fundamental (F) and the first overtone (1O). At the same time, observations of pulsating stars have clearly demonstrated that in most domains only one of the unstable modes can persist at finite amplitude. While no certain method has yet been found to discern the pulsation mode of any given star, theoretical studies have succeeded in dividing various instability-strip domains determined by properties of modal selection (e.g., Christy 1966 and Stellingwerf 1975a for the RR Lyrae stars; Stobie 1969 and King et al. 1973 for the classical Cepheids). Generally, these studies have agreed upon at least three regimes of different finite-amplitude behavior: (1) a region, beginning at the 1O blue edge and continuing somewhat beyond the F blue edge, where only 1O will persist; (2) a middle-temperature region where either F or 1O may be selected, depending upon initial conditions; and (3) an F only domain, still further to the red.

For the RR Lyrae case, such classifications seem to be consistent with certain observed properties, notably the Oosterhoff dichotomy (Stellingwerf 1975a). Similarly, for the middle-period or “bump” Cepheids, it appears that the modal selection categories are at least not in conflict with the observed Hertzsprung sequence (interpreted as involving fundamental mode pulsators), although severe conflicts may exist with the theory of stellar evolution (e.g., Simon and Schmidt 1976).

In spite of the partial successes that have been obtained, the theory of modal selection remains in a rather unsatisfactory state. Modal transition boundaries delineated in some of the studies have been sharply criticized (e.g., Cox 1979), while the physics underlying the modal selection problem remains as obscure as ever. The latter shortcoming is strongly underlined by our failure so far to deal satisfactorily with the phenomenon of multimode pulsation, whether in the regime of the double-mode Cepheids, or near the main sequence where the δ Scuti and AI Velorum pulsators are found.

In recent years, the advent of nonlinear, periodic integration techniques (Baker and von Sengbusch 1969; Stellingwerf 1974) has held out the promise of a new approach to the problems of modal selection. Stellingwerf (1975a, b) tested the stability of single-mode limit cycles and proposed modal selection categories on the basis of whether or not perturbations
corresponding to one of the modes would grow around the limit cycle of the other. Thus, when $F$ grows in $10$, but $10$ fails to grow in $F$, the fundamental is selected at limiting amplitude, and vice versa. When both limit cycles are stable, the final state depends upon initial conditions. Further, Stellingwerf suggested that the case of instability of both limit cycles ought to correspond to double-mode pulsation.

While the above ideas have been tested by nonlinear initial-value integrations in a handful of cases, they remain open to question for a number of reasons. In the first place, different results have sometimes been obtained by different workers treating the same models (e.g., Stellingwerf 1975b; Cox, Hodson, and Davey 1976; Hodson and Cox 1976). Furthermore, since the periodic integration technique will not necessarily detect all limit cycles, and certainly cannot find aperiodic final states, some doubt must arise as to both the necessity and sufficiency of Stellingwerf’s categories. For example, if $F$ grows in $10$ but not vice versa, what is to guarantee that both modes will not persist after many cycles? Or, if both limit cycles are stable for a given model, how can it be ruled out that for certain initial conditions an aperiodic final state might also be reached? Clearly, such questions must be answered before the claim can be justified that periodic integration techniques can predict limiting-amplitude modal behavior.

An alternate approach to the problem of nonlinear pulsations involves the iterative theory (Simon 1972) which provides a means for calculating higher-order corrections to the linear pulsation quantities. A recent extension of this theory (Simon 1980, hereafter S80) has allowed the simultaneous treatment of two modes to second order, including lowest order modal interactions.

In an early paper, Simon and Sastri (1972) demonstrated, for the adiabatic case, that the second-order iterative correction terms are strongly influenced by resonances in the linear normal mode frequency spectrum. Later, this result was extended to nonadiabatic single-mode pulsations in classical Cepheid models (Simon 1977) and to the double-mode case (S80). At the same time, Simon (1979a) has suggested that the narrow range of period ratio observed in both the double-mode Cepheids and the double-mode Al Velorum stars is attributable to the influence of the interaction resonances $\omega_1 + \omega_0 = \omega_3$ and $\omega_1 + \omega_0 = \omega_4$ in the former and latter cases, respectively.

In the present investigation we study the problem of modal selection in a series of double-mode Cepheid models with period ratios close to the observed value ($P_1/P_0 \approx 0.70$), and lying in the vicinity of the resonance $\omega_1 + \omega_0 = \omega_3$. The aim of this work is twofold: first, to test the resonance hypothesis of Simon (1979a) in a specific case; second, to attempt to shed further light on the general problem of modal selection. Our procedures and results will be described in §II, while §§III and IV will be given over to interpretation and discussion, including a semiquantitative description of modal selection based upon the iterative theory.

II. HYDRODYNAMIC INTEGRATIONS

a) Models and Techniques

The hydrodynamic integrations were performed with the code DYNSTAR, operating in both its initial value (Hodson and Cox 1976) and periodic (Cox, Hodson, and Davey 1976) modes. The models chosen for integration came from the principle series of S80, viz., $M = 3.3 M_\odot$, $L = 1500 L_\odot$, $X = 0.70$, $Z = 0.02$. Although convection may well be important in some of the cooler models, we have omitted it to make the calculations more manageable.

We note that the S80 and DYNSTAR calculations do not correspond precisely, since the static and linear nonadiabatic (LNA) models employed to initialize DYNSTAR differed slightly (and unavoidably) from the S80 versions for the same parameters and physical assumptions. Table 1 shows how these differences affected the linear period ratios $P_1/P_0$, the linear amplitude growth rates $\epsilon_1$ and $\epsilon_{11}$ (measured in percent per period) and the normalized distance to the resonance center, $d_3$ (Simon 1979a) for two specific models. In particular, one sees that the resonance center, $d_3 \approx 0$, is moved coolward some 150 K by DYNSTAR as compared with its location in the models of S80. We shall refer again to this circumstance later.

During the initial-value phase of the hydrodynamic calculations, the changing modal content of the oscillations was monitored by fitting the photospheric velocity variations with a third-order nonlinear Fourier-interaction series in which the two basic periods, $P_0$ and $P_1$, were also free parameters (Simon 1979b). Each of these fits included about 500 to 1000 time points. For models initiated at small amplitude, these points would, at the outset, encompass as many as 100 fundamental periods; but later, as limiting amplitude was approached, the points would cover only 10 fundamental periods, or even fewer. Standard deviations for these fits were typically less than 2 km s$^{-1}$, as compared with limiting amplitudes of 40 or 50 km s$^{-1}$.

<table>
<thead>
<tr>
<th>TABLE 1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LNA Period Ratios and Growth Rates:</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>PARAMETER</td>
</tr>
<tr>
<td>$P_0$</td>
</tr>
<tr>
<td>$P_1/P_0$</td>
</tr>
<tr>
<td>$\epsilon_1$</td>
</tr>
<tr>
<td>$\epsilon_{11}$</td>
</tr>
<tr>
<td>$d_3$</td>
</tr>
</tbody>
</table>

* Measured in percent per period.
The question of exactly which properties of a given fit should be used to determine modal content has been answered differently by different investigators (e.g., Faulkner 1977; Cox, Hodson, and King 1978; Hodson, Stellingwerf, and Cox 1979; Shobbrook and Faulkner 1979). In the present study, we have monitored the amplitudes of the two basic frequencies, $\omega_0$ and $\omega_1$ (these amplitudes are called $A_{0,1}$ and $A_{1,0}$, respectively, in the notation of Simon 1979b), ignoring the harmonics and interaction terms which also emerge from the third-order fits. This interpretation is in line with the iterative theory in which the lower and higher order terms scale in a fixed pattern (Simon 1972), so that the amount present of $A_{0,1}$ and $A_{1,0}$ also determines the harmonic and interaction amplitudes. Furthermore, it is the lowest-order quantities which are needed for the comparisons we shall make with growth rates from LNA theory. In any event, since our interests are served by merely knowing the crude growth or decay rate for each mode at a given time (as opposed to a precise breakdown of the modal content), the results we shall report will be little influenced by our specific choice of monitoring technique.

**b) Initial Conditions**

The initial-value hydrodynamic integrations were all started by imposing velocity eigenfunctions from the LNA treatment of the respective models. The pulsations were initiated at small amplitude, characterized by a maximum photospheric velocity of 1 km s$^{-1}$. The initial velocity distributions were of two kinds: (1) the “half and half,” in which the F and 1O eigenfunctions were superposed, each scaled to a photospheric value of $\frac{1}{2}$ km s$^{-1}$; and (2) the “pure F,” which consisted of the fundamental eigenfunction alone, scaled to 1 km s$^{-1}$ at the photosphere. We note that in both cases the initial distributions will inevitably contain some degree of noise, thus including a small amount of power at the frequencies of all the normal modes.

**c) Preliminary Calculations**

To begin our investigation, models at 5800, 5550, and 5500 K were initiated at small amplitude in the “half and half” condition. In each of these cases the pattern observed was the same: (1) an initial growth of each of the modes at respective rates consistent with those given by LNA theory, followed by (2) an abrupt quenching of the fundamental as the first overtone leveled off near limiting amplitude. Thus despite the proximity of these models to the resonance $\omega_1 + \omega_0 = \omega_3$, persistent double-mode behavior was not discovered.

Continuing our calculations, we initiated the 5500 K model at small amplitude with the “pure F” distribution. In this case the final outcome was opposite to that described above in that, following the initial phase of linear growth, the fundamental was able to establish itself at full amplitude, while the first overtone was extinguished.

Figure 1 shows the time evolution of the F and 1O amplitudes for both the “half and half” and “pure F” initiations in the model at 5500 K. One is struck by the abrupt switch from growth to decay of the “unwanted” mode, particularly 1O in the “pure F” initiation. The two cases plotted in Figure 1 obviously indicate that initial value integrations for the model in question will lead to different final states depending upon initial conditions. In the terminology of Stellingwerf (1975a), this ought to correspond to the case in which both limit cycles are stable. To check this, we employed DYNSTAR in its periodic mode to determine limit cycles for both F and 1O. Each did indeed turn out to be stable.

Table 2 compares some initial growth rates determined from the hydrodynamic integrations (HYD) with those given by LNA calculations also produced by DYNSTAR. The HYD rates were read crudely from curves like those given in Figure 1. We note from Table 2 that the HYD values are less than their LNA counterparts by amounts ranging from 25 to 50%.

The discrepancies are smaller at 5500 K where the zoning of the LNA version (50 zones) approximated the HYD zoning, than at 5800 K where the LNA model had 195 zones. When one takes into account differences between LNA and HYD numerics along with the approximate method of determining HYD growth rates, the agreement seems good enough to allow the assertion that the initial growth of the hydrodynamic amplitudes crudely agrees with that predicted by LNA.
theory. One may further read from Table 2 the reassuring result that initial hydrodynamic growth rates for each mode were essentially independent of initial conditions in the model at 5500 K.

### III. A THEORY OF MODAL SELECTION

We begin this section by considering the hydrodynamic integrations for the 5500 K model, displayed in Figure 1. These results seem to indicate that the mode which reaches the nonlinear regime first is the one which ultimately becomes established. Thus, an initial velocity distribution of equal parts F and IO favors the latter due to its larger linear growth rate, while imposition of “pure F” (i.e., with a small, inevitably present, mixture of IO and other modes) gives the fundamental enough of a head start to overcome the more rapid rise of the overtone. This description appears to be consistent with the results of King et al. (1973), who found that initially imposed fundamental velocity distributions would establish themselves at full amplitude unless the linear growth rate of IO was relatively large, in which case the overtone was selected.

A useful perspective on these results may be obtained by considering the simpler case of the approach to limiting amplitude for a single mode. We may give a heuristic picture of the process as follows: The oscillation is driven from “beneath” by the linear instability and damped from “above” by the nonlinear corrections. Since the relative size of the nonlinear terms is a function of amplitude, the limiting amplitude is reached when nonlinear damping just balances linear driving.

Applying this picture to the case of bimodal pulsations, one finds that it suffices only for the established mode. The other, “unwanted” mode abruptly loses its “linear support” and is thus extinguished. We shall try to further model this process using the iterative theory. We recall that, in this scheme, the pulsation is built up, order by order, beginning with the two basic frequencies $\omega_0$ (fundamental) and $\omega_1$ (first overtone). The relative importance of the various orders is determined by the amplitude of each mode which may be measured by a pair of scale factors—$\lambda_o$ for the fundamental, and $\lambda_1$ for the overtone. The terms of first order scale like $\lambda_o$ or $\lambda_1$, the second-order terms like quadratic products of these factors, the third-order terms like cubic products, etc. Table 3 shows the frequencies which emerge, and their scaling, up to third order.

One notes that the frequencies appearing in Table 3 are linear combinations of the two basic frequencies ($\omega_0$ and $\omega_1$) and are, in fact, the same as those which are obtained from Fourier fitting of observed light curves (Simon 1979b and references therein). For our purposes the important fact to notice from Table 3 is that in third order the original frequencies reappear, so that corrections are added to the amplitudes and phases of the linear eigenfunctions. Furthermore, it can be seen that these corrections are of two distinct sorts: (1) harmonic terms, which involve only the scale factor of the mode being corrected; and (2) interactive terms, which involve both scale factors.

Table 4 shows the scaling of the linear terms and corresponding third-order corrections, for each of the two basic frequencies. In the simplest possible interpretation, the third-order corrections damp the pulsation by distorting the linear eigenfunctions until they can no longer produce net driving. In this sense, the harmonic corrections are to be associated with the single-mode case, described heuristically above. The competition between linear driving and nonlinear harmonic damping is decided only by the scale factor of the mode in question, i.e., by its amplitude.

On the other hand, one sees from Table 4 that the ratio of interactive damping to linear driving depends not upon the amplitude of the mode considered, but rather upon that of the competing mode! Thus there

### TABLE 2

**Linear and Nonlinear Growth Rates**

<table>
<thead>
<tr>
<th>MODE</th>
<th>INITIATION</th>
<th>GrowTH RATES$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>Half and half</td>
<td>1.44 2.42</td>
</tr>
<tr>
<td>IO</td>
<td>Half and half</td>
<td>2.59 4.20</td>
</tr>
<tr>
<td>T$_e$ = 5800 K</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>Half and half</td>
<td>2.49 3.44</td>
</tr>
<tr>
<td>F</td>
<td>Pure F</td>
<td>2.72 3.44</td>
</tr>
<tr>
<td>IO</td>
<td>Half and half</td>
<td>2.86 4.21</td>
</tr>
<tr>
<td>IO</td>
<td>Pure F</td>
<td>2.68 4.21</td>
</tr>
<tr>
<td>T$_e$ = 5500 K</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^a$ Measured in percent per period.

### TABLE 3

**Frequencies Up to Third Order in the Iterative Theory**

<table>
<thead>
<tr>
<th>ORDER</th>
<th>FREQUENCY</th>
<th>SCALING</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\omega_0$</td>
<td>$\lambda_0$</td>
<td>Linear</td>
</tr>
<tr>
<td>2</td>
<td>2$\omega_0$, 0</td>
<td>$\lambda_0^2$</td>
<td>Harmonic</td>
</tr>
<tr>
<td>3</td>
<td>$\omega_1 + \omega_0$, $\omega_0$</td>
<td>$\lambda_0^2 \lambda_1$</td>
<td>Interactive</td>
</tr>
<tr>
<td>4</td>
<td>$3\omega_0$, $\omega_0$</td>
<td>$\lambda_0^3$</td>
<td>Harmonic</td>
</tr>
<tr>
<td>5</td>
<td>$\omega_1$, $\omega_1$, $\omega_1$</td>
<td>$\lambda_1^3$</td>
<td>Harmonic</td>
</tr>
<tr>
<td>6</td>
<td>$2\omega_0 + \omega_1$, $\omega_1$</td>
<td>$\lambda_0^2 \lambda_1^2$</td>
<td>Interactive</td>
</tr>
<tr>
<td>7</td>
<td>$2\omega_1 + \omega_0$, $\omega_0$</td>
<td>$\lambda_0^2 \lambda_0$</td>
<td>Interactive</td>
</tr>
<tr>
<td>8</td>
<td>$\omega_1$, $\omega_0$, $\omega_0$, $\omega_0$, $\omega_0$</td>
<td>$\lambda_0^3 \lambda_1^2$</td>
<td>Interactive</td>
</tr>
</tbody>
</table>

### TABLE 4

**Scaling of Linear Amplitudes and Third-Order Corrections in the Iterative Theory**

<table>
<thead>
<tr>
<th>FREQUENCY</th>
<th>FIRST ORDER</th>
<th>THIRD ORDER</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega_0$</td>
<td>$\lambda_0$</td>
<td>$\lambda_0^2$</td>
</tr>
<tr>
<td>$\omega_1$</td>
<td>$\lambda_1$</td>
<td>$\lambda_1^3$</td>
</tr>
</tbody>
</table>
must exist some value of $\lambda_1$ (say $L_1$) beyond which the fundamental will be interactively damped, and some value of $\lambda_0$ (say $L_0$) beyond which the overtone can no longer maintain itself. If we now define the single-mode limiting amplitudes for $F$ and $10$ as $A_0$ and $A_1$, respectively, four distinct categories emerge from the analysis:

a) $A_1 > L_1$, $A_0 < L_0$. In this case, $F$ will be suppressed before $10$ reaches its limiting amplitude, but not vice versa. Thus the final state must be $10$. This case is exactly equivalent to Stellingwerf’s (1975a) category (expressed in terms of growth rates of one of the modes about the limit cycle of the other): $10$ in $F > 0$, $F$ in $10 < 0$.

b) $A_1 < L_1$, $A_0 > L_0$. This is just the opposite of case (a), and is equivalent to Stellingwerf’s $10$ in $F < 0$, $F$ in $10 > 0$.

c) $A_1 > L_1$, $A_0 > L_0$. Here either mode is capable of suppressing the other, provided it can become large enough before being suppressed itself. Thus the mode which wins the race to finite amplitude will ultimately establish itself. Clearly, the 5500 K model discussed above falls into this category which is equivalent to Stellingwerf’s $10$ in $F < 0$, $F$ in $10 > 0$.

d) $A_1 < L_1$, $A_0 < L_0$. Here neither mode can suppress the other. According to Stellingwerf, this is the case of double-mode pulsation, characterized by $10$ in $F > 0$, $F$ in $10 < 0$.

Consider now a hypothetical experiment in which one of the modes (say $10$) is held fixed at a given amplitude ($\lambda_{10}$) while the other mode (in this case $F$) is left free to seek a limit. Repetition of this experiment on a given model will produce a function $\Lambda_0(\lambda_{10})$. In a similar way, reversing these roles determines a function $\Lambda_1(\lambda_0)$. We thus introduce the concept of the limiting amplitude of a given mode as a function of the (fixed) size of the other mode.

Figures 2a–2d show schematic representations of the functions $\Lambda_0(\lambda_{10})$ and $\Lambda_1(\lambda_0)$. In each case, the former (solid curve) is plotted against the ordinate $\lambda_1$, and the latter (dashed curve) against the abscissa $\lambda_0$. To obtain the general form of the graphs given in Figure 2, the simplest possible assumptions have been made—namely, that both functions are strictly monotonic and that they cross at most once. The former assumption corresponds physically to the circumstance in which the interactive third-order corrections always alter the linear eigenfunctions in such a way as to reduce the driving, no matter what the size of $\lambda_0$ or $\lambda_1$.

It can be easily seen that Figures 2a, 2b, 2c, and 2d correspond, respectively, to the modal selection categories (a), (b), (c), and (d), given above. The single-mode limiting amplitudes $\Lambda_0(0)$ and $\Lambda_1(0)$, as well as the suppression amplitudes $L_0$ and $L_1$, have been entered schematically. Arrows on the diagrams crudely indicate the evolution direction of system points ($\lambda_1, \lambda_0$) in various regions of the amplitude-amplitude space. In Figure 2c, a double-mode pulsation point exists where the two curves intersect, but this point is unstable. On the contrary, the intersection in Figure 2d is a stable point of double-mode pulsation. As indicated by the arrows for this case, the system must eventually relax to a bimodal state.

Thus, provided that the functions $\Lambda_0(\lambda_{10})$ and $\Lambda_1(\lambda_0)$
are indeed monotonic and cross not more than once, the Stellingwerf categories will be absolute, and, in particular, the criterion for double-mode pulsation (i.e., instability of both limit cycles) will be both necessary and sufficient. On the other hand, there is no a priori reason to believe that the interactive terms will necessarily be damping at all amplitudes for all models. If we abandon this assumption, then the possibility exists of diagrams much more complex than those displayed in Figure 2. In particular, one may easily construct cases in which a system point in the amplitude-amplitude diagram executes cyclic evolution around an intersection of the functions \( \Lambda_0(\Lambda_1) \) and \( \Lambda_1(\Lambda_0) \). Such an evolution could explain the modal changes which seem to be occurring in TU Cas (Hodson, Stellingwerf, and Cox 1979; Niva 1979) and perhaps in U TrA (Shobbrook and Faulkner 1979). Of course, if this suggestion is correct, we must expect to see at some time in the future a reversal in the direction of modal evolution in these two stars.

The interpretations presented in this section may be made more concrete by a further examination of the initial-value integrations for the model at 5500 K. In Figure 3, the data from these integrations (already presented in Fig. 1) have been replotted in amplitude-amplitude space. The quantities \( \Lambda_0^1 \) and \( \Lambda_1^0 \) refer to the F and \( 1^0 \) amplitudes, respectively. One sees that approximate values for the crucial limits \( \Lambda_0(0) \), \( \Lambda_1(0) \), and \( \Lambda_0^1 \), may be read directly from this graph. These have been indicated. It is interesting to note along the ordinate of this plot the relatively small distance separating \( \Lambda_1(0) \) and \( \Lambda_0(0) \). Since it is the sign of the quantity \( \Lambda_0(0) - \Lambda_1(0) \) which distinguishes category (b) from category (c), one might suspect that the 5500 K model does not lie too far from a modal transition line. To test this proposition, periodic integrations using DYNSTAR were performed on a model with \( T_e = 5300 \) K. The fundamental limit cycle was found to be stable; the overtone limit cycle, unstable. Thus the transition between (b) and (c) behavior was found to lie between 5500 and 5300 K.

IV. DISCUSSION

Up to this point, we have studied the growth of pulsations in a handful of models, and offered an interpretation of the modal selection process based on the iterative theory. No evidence has been found for stable double-mode pulsation in any of the models tested despite their proximity to the resonances \( \omega_1 + \omega_0 = \omega_3 \) and \( P_2/P_0 = 0.5 \). Nevertheless, we shall argue in what follows that the prognosis for the resonance hypothesis is perhaps not so dim as these negative results might indicate.

Figure 4 shows fundamental and first overtone growth rates (in percent per period) plotted against effective temperature over a range of models. The two lower curves come from periodic integrations using...
DYNSTAR and represent the growth rates of $F$ in $\Omega_0$ and $\Omega_1$ in $F$, respectively. The two upper curves give linear growth rates calculated with the finely-zoned models of S80. The latter curves have been shifted to the right by 150 K in order to match up DYNSM and S80 period ratios as well as possible (see § II). The approximate locations of the two resonance centers are indicated at the top of the diagram.

The most interesting of the curves in Figure 4 is the one representing the growth of first overtone perturbations about the fundamental limit cycle ($\Omega_1$ in $F$). While these perturbations suffer extremely strong damping in the model at 5500 K, by the time the 5200 K model is reached this damping has weakened considerably. The rise of the $\Omega_1$ in $F$ curve is qualitatively in agreement with the results of Stellingwerf (1975a, b). In fact, had the maximum of this curve crossed the zero line, a narrow region of double-mode pulsation would have been indicated according to Stellingwerf's categories. On the other hand, we note that our $\Omega_1$ in $F$ curve turns down slightly after reaching a peak, in contrast to the Stellingwerf calculations where the curve continues to rise. This downturn could be consistent with the results reported by Cox, Hodson, and Davey (1976).

The powerful damping encountered at 5500 K may be attributed to the fact that this model represents the estimated center of the interaction resonance $\omega_1 + \omega_0 = \omega_3$ for the DYNSM series. (The calculated center occurs at ~5650 K for the models of S80.) Figure 5 shows the interior run of the second-order interaction amplitude $\mu_{1+}$ in the 5650 K model of S80. The trinodal resonant structure is evident (see S80). We note that the interaction amplitude is extremely strong, not only in the H I ionization zone, but also near the He II ionization zone, and even further inward (compare, e.g., the runs of $\mu_{1+}$ given in Figs. 5 and 6 of S80). If, in the simple interpretation of the previous section, the interaction terms always provide damping, then it is not surprising that this damping should be most effective when the interaction is strongest.

As one moves coolward of the resonance center, the interaction begins to weaken. However, a competing effect may be noted from Figure 4—namely, that the linear driving in $\Omega_0$ also begins to decline. In our interpretation, it is the former of these effects that produces the rise of the $\Omega_1$ in $F$ curve, and the latter that gives rise to the subsequent downturn.

For the fundamental, the situation is somewhat different. At 5500 K, where the interaction is strongest, the fundamental is still suppressed ($F$ in $\Omega_0 < 0$), but by the time one reaches the 5300 K model, the
transition line has already been crossed and F is able to grow in IO. In contrast to the downturn noted in the IO in F curve, the F in IO curve continues to rise. Presumably, this is due to the fact that the linear driving in F has not yet saturated (see Fig. 4). In addition, the iterative interpretation suggests that, in general, interactive damping ought to suppress IO more effectively than it suppresses F. The reason for this is that the third-order interactive corrections to F (see § III) arise from the interaction of certain second-order terms with the linear eigenfunction of IO, while the corrections to IO involve the interaction of the same second-order terms with the linear eigenfunction of F. Since the fundamental linear eigenfunction is everywhere larger than that of the overtone, it follows that the interactive damping of IO ought to be favored.

As a final illustration of connections which appear between the resonance-influenced iterative amplitudes of S80 and the present hydrodynamic calculations, we wish to consider the DYNSTAR model at 5150 K (~ 5300 K in S80). The period ratio for the S80 version of this model is $P_2/P_0 = 0.498$ which puts it very near the center of the harmonic resonance. Figures 6a and 6b show the fundamental limit cycle at the photosphere of this model in radial velocity and $M_{\text{bol}}$, respectively. (The former plot is made in "observational" coordinates.) One sees from these curves a clear reinforcement of the idea that Cepheid "bumps" are connected with the resonance $P_2/P_0 = 0.5$, the double maximum structure appearing, as predicted, near the resonance center (Simon and Schmidt 1976; Simon 1977).

In addition, it is interesting to note that the limiting amplitudes for the 5150 K model displayed in Figure 6 are noticeably smaller than those attained by slightly hotter models. (For example, in the DYNSTAR model at 5300 K, the peak-to-peak velocity amplitude is about 52 km s$^{-1}$, while $\Delta M_{\text{bol}} \sim 1.0$.) This dip in amplitude is actually observed at a period of approximately 10 days in the classical Cepheids (Ledoux and Walraven 1958; van Genderen 1974). In the iterative interpretation, it may be explained as the result of enhanced harmonic (i.e., single-mode) damping occasioned by the great strength of the second-order harmonic correction ($\beta_1$, in the notation of S80; see Fig. 7 of that paper) in models near the resonance center.

Finally, we remark that the redward rise of the IO in F curve (Fig. 4) gives some hope that models not too different from the present ones may yet be successful in satisfying the Stellingwerf criterion of instability of both limit cycles. One possible alteration which comes to mind involves the artificial viscosity, whose effects on modal selection still require detailed examination. The results of the present investigation, while, strictly speaking, negative with respect to the resonance hypothesis, have tentatively established a relationship between resonances and modal selection and produced models which tend toward double-mode pulsation in the region between $\omega_1 + \omega_0 = \omega_3$ and $P_2/P_0 = 0.5$. The above results suggest that this domain of resonant interaction ought to be explored further.

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