PART III

LARGE MASS STARS, STABILITY IN SUPERGIANTS, CRITICAL MASSES

NON-LINEAR INSTABILITY OF STARS WITH $M > 100\ M_\odot$

J. C. B. PAPALOIZOU* and R. J. TAYLER
Astronomy Centre, University of Sussex, England

Abstract. Massive main sequence stars are vibrationally unstable to small perturbations excited in the region of nuclear energy generation. This instability may, however, be limited at finite amplitude. Only the fundamental radial mode is unstable with an *e*-folding time of 10^5 to 10^6 pulsation periods; in contrast the overtones have damping times short compared with the growth time of the fundamental. Non-linear effects couple the linear modes. At very low amplitude the energy transfer time between modes is long compared with both growth and damping times and, as the overtones decay, a pure fundamental should result. However, as the amplitude increases, the transfer time becomes less than the growth and damping times. Energy can then be transferred from the fundamental to the overtones and damping can lead to a limitation of amplitude.

As integration for 10^6 periods is impossible, this behaviour cannot be verified by direct calculation. Several authors have integrated modified equations in which the excitation and damping have been speeded up considerably and they have found that non-linear effects limit the instability. They have not, however, found that overtones play any role. Papaloizou (1973a, b) has used the same technique to obtain an initial non-linear solution but he has then integrated the unmodified equations. He has found that, if the amplitude is high enough, overtones rapidly appear and, moreover, the most prominent overtone is one whose frequency is close to being an integral multiple of the fundamental frequency. It appears from his calculations that stabilization occurs at an even lower amplitude than previously suggested.

He has since studied non-radial modes in massive stars, although he has not yet performed detailed non-linear calculations. He has found that radial and non-radial modes in rotating massive stars are strongly coupled even for quite slow rotation speeds. This is particularly true for the overtones where the frequencies of radial and non-radial modes are very close and this coupling could be very important in the non-linear development of the vibrational instability.

Although the excitation mechanism in δ Scuti variables is very different from that in the massive stars, this is again a situation in which the *e*-folding time is 10^5 to 10^6 periods. Once again it is possible that there will be complicated behaviour due to coupling between the fundamental and the overtones, with non-radial oscillations playing a role in rotating stars.

* Present address: Department of Astrophysics, Oxford, England.

Ledoux et al. (eds.), Stellar Instability and Evolution, 77–79.

References

Papaloizou, J. C. B.: 1973a, *Monthly Notices Roy. Astron. Soc.* **162**, 143.
Papaloizou, J. C. B.: 1973b, *Monthly Notices Roy. Astron. Soc.* **162**, 169.

DISCUSSION

Cox: Does Papaloizou get larger or smaller limiting amplitudes for these massive stars than Talbot, Appenzeller or Ziebarth?

Tayler: The amplitude would be rather lower: the stabilization would occur at a lower amplitude than that predicted by Talbot, Appenzeller and Ziebarth. Papaloizou gets more rapid stabilization due to this transference of energy to the overtones, but he generally confirms the results of Appenzeller, Ziebarth and Talbot. I can't remember what his amplitude was, because I can't remember what the mode looks like. What I can remember is that when the ratio $\delta r/r$ at the centre is 0.04, he is already getting damping of the oscillation. Having got this thing into a finite amplitude you can't watch long enough either to see it grow or decay, so in order to decide whether it's decaying or growing, he has to use a generalisation of the energy integral that's used for the linear oscillations to find what the *e*-folding time or decay time is. Using that, he predicts that the thing is already decaying at one amplitude and growing at an amplitude a bit below that.

Iben: Didn't Appenzeller suggest that mass was shot off in these objects as a result of shockwaves?

Tayler: Papaloizou would say that as he gets a limiting amplitude which is rather lower than the other people, these effects might be rather less. He hasn't done a very detailed atmospheric calculation; no more than anybody else has. I think the estimates that Appenzeller and the others made of mass loss was done rather crudely. That's not a criticism, it's a comment on how difficult it is to try and put a proper atmosphere on to a pulsating star of any sort, let alone one of these rather awkward ones.

Aizenman: If the computations were to be carried out for times long énough for the overtones to die away, would the behaviour of the light curves then become similar to those of either Appenzeller or Ziebarth?

Tayler: He was worried about that very point. Any transients due to the overtones will not decay for a very long time, but the point that makes him relatively confident in his results, is that the only overtones he gets are always the overtones which are closest to resonance. If it was purely transience, he would expect it to be an arbitrary overtone. In other words, if you change the mass of the star then you find a different overtone is close to resonance, and as you crank up the mass of the star, you first get one bump on the ascending light curve, then 2 then 3 then 4 and then as you crank up the mass again, it starts going down again because the modes come into resonance in the opposite order. It would be rather surprising that you would have got this regularity if it was purely transient.

Van Woerden: Do you have any estimates for the amplitude of the light curve?

Tayler: I can't remember.

Aizenman: This is really directed to Art Cox. In your non-linear computations of Cepheids, do you find any behaviour similar to that described in this talk before the star begins to oscillate in a pure overtone?

Cox: No, we don't see this kind of thing.

Stobie: Is there any reason why the periods that you've calculated are from linear theory and not from non-linear calculations; is it because of the great length of time of the decay period?

Tayler: I think so.

Sargent: Might I ask what kind of stars in nature these objects are supposed to correspond to?

Tayler: The P Cygni's for instance, might be at the lower end of our model sequence, but as I say, it started off really as a fundamental theoretical problem: is there any reason why there shouldn't be more massive stars than are observed? That was the original idea. Well, now this would suggest that if there *aren't* more massive stars, it's either because the mass function peters out or because star formation will not allow such massive stars, and I know Larson has published papers in which he said you couldn't get a star this massive formed anyway. But, of the real stars, the P Cygni's are the ones that are nearest this region.

Cox: Is this paper disputing Larson's results?

Tayler: No, because this paper isn't considering the formation, only considering what would happen if you once got one.

Bessell: If the current evolutionary models of John Robertson are correct, then the stars in the LMC which have visual magnitudes around 10th magnitude are likely to be above 65 solar masses. These stars are about 2 mag. brighter than the 65 $M_\odot$ stars in Scorpius.

Tayler: Do they have any irregularities in their behaviour?

Bessell: They certainly do.

Tayler: They do – good (laughter).