RECENT WORK ON CEPHEID VARIABLES

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ABSTRACT

Recent work on Cepheids is reviewed in the areas of (1) the large-amplitude mode behavior, (2) convection, and (3) Cepheid masses. Initial-value type nonlinear calculations have not yet yielded true double-mode behavior. Yet we have the beginnings of a promising theory of modal selection. Theoretical calculations also yield reasonably located red edges to Cepheid (and Cepheid-like) instability regions.

Recent observational results have led to increased values of the "pulsation mass," so that this mass is now in fair agreement with evolution theory. The "Wesselink mass" is also satisfactory. Thus now only "bump" and "beat" masses are possibly discrepant. Some possible ways which have been suggested to alleviate these discrepancies are reviewed. The proposal of helium enrichment in the outer stellar layers can apparently satisfactorily resolve the beat (and perhaps also the bump) mass anomaly. A recent suggestion that part of the pressure in the envelope is due to a tangled magnetic field (not unusually strong) resolves the above mass anomaly about as well as the helium-enrichment idea does.

Recent results regarding duplicity and period changes in Cepheids are reviewed.

1. INTRODUCTION

In the opinion of this reviewer, there are still three main problems connected with classical Cepheids (and Cepheid-like variables). These are (1) the large-amplitude mode behavior, (2) convection, and (3) Cepheid masses. Recent reviews are by J. Cox (1980 and 1979).

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2. SOME OUTSTANDING PROBLEMS

2.1. Large-Amplitude Mode Behavior

Here the basic question is the following. Suppose a star or stellar model is found by means of a linear theory to be unstable to two or more pulsation modes. Then, at large amplitudes, where nonlinear effects are important, which one (or ones) of the above unstable modes will be present?

Past nonlinear numerical work seems to have reached agreement on at least three types of limiting-amplitude mode behavior: (1) first harmonic (1O) only; this behavior is characterized by relatively high effective temperatures, beginning at the 1O blue instability edge and continuing somewhat beyond the fundamental (F) blue edge. (2) Either F or 1O, depending on initial conditions; this behavior is characterized by intermediate effective temperatures. (3) F only; this behavior is characterized by relatively low effective temperatures. However, as is stated in Simon et al. (1980), the physics underlying modal selection is as obscure as ever.

A promising step toward the resolution of this important question has been made by Simon (Simon et al. 1980), on the basis of the iterative theory (Simon 1972a,b). Simon's approach leads to four possible types of large-amplitude mode behavior, which are the same as those due to Stellingwerf (1975). The first three of these types correspond to the three types of large-amplitude mode behavior discussed above. The fourth type corresponds to a situation in which each mode (F or 1O) is unstable to a switch-over to the other mode. This type of behavior Stellingwerf (1975) associated with double-mode pulsation. Simon also concludes that this type should correspond to double-mode pulsation, but discusses some reasons why this behavior may possibly not be realized in actual stellar models.

On the other hand, Faulkner and Shobbrook (1979) state that this type of behavior may correspond to a continuous switching back and forth from one mode to the other.

It has been suggested by Simon (1979) that double-mode behavior is a resonance effect: such behavior occurs only when the "interactive" angular frequency $\omega_0 + \omega_1$ of the F and 1O equals the frequency ω_3 of the third overtone (for the double-mode AI Velorum stars this last frequency is ω_4, the frequency of the fourth overtone).

In a numerical experiment designed to test Simon's (1979) suggestion, initial-value integrations were carried out by Simon et al. (1980) using a model whose characteristics put it very close to the resonance $\omega_0 + \omega_1 = \omega_3$; the model also had the ratio of 1O to F periods, Π_1/Π_0, close to the observed value, 0.70, for beat Cepheids (Stobie 1977). This model (or any models close to it) failed to exhibit true double-mode behavior. However, arguments are presented to the effect that these negative results do not necessarily invalidate the basic idea.

These ideas regarding resonances have been confirmed by Petersen (1979). This resonance $\omega_0 + \omega_1 = \omega_3$ is discussed in greater detail by Simon (1980). However, it should be emphasized (as has been stressed by A. Cox 1980) that the failure, so far, of initial-value nonlinear calculations to yield true double-mode behavior may itself constitute a significant problem.

Of course, another possibility is that the beat Cepheids are merely switching modes. In fact, Hodson et al. (1979) and Niva (1979) found that the amplitude of the 1O for TU Cass has diminished somewhat over the past 67 years. Also, Faulkner and Shobbrook (1979) found that the 1O in U Tr A was growing in amplitude. But, if these stars are switching modes, one wonders why some 25% of all Cepheids with short periods (say two to seven days) are beat Cepheids (Stobie 1977). In view of the short switching times (~80 years, according to Stellingwerf 1975), one would in this case expect only a small fraction of all Cepheids in this period range to be beat Cepheids.

2.2. Convection

Perhaps the most pressing question about stellar envelope convection concerns whether or not it will actually "quench" pulsation on the red side of the Cepheid instability strip.

Deupree (1980) has extended his two-dimensional nonlinear calculations (Deupree 1975a,b; 1976a,b,c; 1977a,b,c,d) to the determination of the red edge of the Cepheid instability strip. He finds that convection will indeed quench pulsations on the red side of this strip, just as on the red side of the RR Lyrae region of instability.

The difficult problem of the interaction of convection and pulsation has been investigated in linear theory by Baker and Gough (1979), Gonczi and Osaki (1980), and Saio (1980). These investigations have all been based on some approximation or extension (Unno 1967) of the mixing length theory.

One of the interesting features of these calculations is that they all show rapid spatial oscillations of thermal quantities, such as temperature perturbation or convective flux, deep within a convective region. The physical origin of these oscillations can be understood fairly readily.

The unphysical nature of these oscillations is acknowledged by Baker and Gough (1979). A smoothing procedure is used to eliminate their effect by Gonczi and Osaki (1980). The equations are modified slightly by Saio (1980), in such a way that the above spatial oscillations do not appear.

Baker and Gough (1979) find that the interaction between pulsation and convection indeed restores stability on the red side of the instability strip. Their red edge is not in close agreement with observations, but its location is at least not unreasonable. On the other hand, Gonczi and Osaki (1980) are less optimistic, and admit that there are difficulties and uncertainties with the linear theory approach. However, in a recent study Gonczi (1980) finds that the introduction of a turbulent viscosity, using a physically plausible model for this viscosity, gives a reasonable red edge. But the exact location of this red edge depends, not surprisingly, rather sensitively on the model chosen for the turbulent viscosity. Nevertheless, we may conclude on the basis of both nonlinear and linear theory that we understand tolerably well the existence of red edges to the Cepheid and RR Lyrae instability regions.

The third problem, Cepheid masses, is discussed at length below.

3. CEPHEID MASSES

Work in recent years, as summarized in the excellent review article by A. Cox (1980), has decreased the severity of the decade old (or more) "Cepheid mass discrepancy," but has not eliminated it.

3.1. Types of Masses

Before proceeding further, it might be appropriate at least to mention the various essentially differing kinds of mass that are associated with a given star (definitions may be found in, e.g., J. Cox 1980). They are evolution, pulsation, Wesselink, bump, and beat masses, and are denoted by M_{evol}, M_Q, M_W, M_{bump} and M_{beat}. In terms of these masses, the above Cepheid mass anomaly may be expressed by saying that the four masses M_Q, M_W, M_{bump}, and M_{beat} are all significantly less than M_{evol}.

3.2. Resolution of the Pulsation and Wesselink Mass Anomalies

As pointed out by A. Cox (1980), two of the above four mass discrepancies no longer exist. They are M_Q and M_W. The former has increased recently, thus making it close to M_{evol}. Hence, now only M_{bump} and M_{beat} are anomalous.

The factor that has caused M_Q to increase is the increase in the radii R of Cepheids. In turn, the increased R values are due to (1) smaller Cepheid reddenings (Pel 1978; Dean et al. 1978; Martin et al. 1979), which result in intrinsically redder Cepheids; (2) somewht more luminous Cepheids, deriving from the increased distance of the Hyades cluster (Hanson 1977).

Data regarding M_Q for the 16 best known calibrating Cepheids have been given by A. Cox (1980). These results show that the ratio M_Q/M_{evol} is now sometimes larger, sometimes smaller, than unity and that this ratio differs from unity by only 10-20% or less in most cases.

Data regarding M_W for a number of Cepheids have also been given by A. Cox (1979, 1980). Despite considerable scatter, the average value of M_W/M_{evol} is about 0.9-1.0 for periods below 10 days, and 0.6-0.7 for periods above 10 days. He suggests that the results imply a genuine mass anomaly above a period of 10 days, due probably to some mass loss in the main sequence or post main sequence B star stages.

3.3. The Bump and Beat Mass Anomalies

Only the M_{bump} and M_{beat} masses now exhibit significant discrepancies with respect to M_{evol}.

It was originally suggested by Christy (1967) that the bumps in the velocity curves of Cepheids with periods around 7^d - 10^d were the result of an "echo." On the other hand, it was proposed by Simon and Schmidt (1976) that the above bumps were produced by a resonance between the fundamental mode and the second overtone, such that the ratio Π_2/Π_0 of the above two periods was close to 0.5.

Simon (1976, 1977) presented further arguments, based on the iterative theory (Simon 1972a,b), that the bumps were produced by a resonance, as explained above. This conclusion is very desirable, for it would imply that anything that would reduce the ratio Π_2/Π_0 would resolve the bump mass anomaly. This conclusion would also, as pointed out by A. Cox (1980), make the bump Cepheids a special case of the beat Cepheids, and both bump and beat mass anomalies might be solved at once.

All mechanisms proposed so far for reducing the two ratios Π_1/Π_0 and Π_2/Π_0 serve to increase Π_0 more than Π_1 or Π_2. Note that the required amount of increase of Π_0 is not large; only a 5-10% increase (assuming that Π_1 and Π_2 are not appreciably changed) would be sufficient to resolve these two mass anomalies, if indeed the bumps are the result of a resonance phenomenon.

The mechanisms proposed so far for reducing Π_1/Π_0 and Π_2/Π_0 are (1) convection in the envelope, (2) rotation, (3) inhomogeneous composition in the envelope, (4) nonradial mode contamination, and (5) a tangled magnetic field. Mechanisms (1) (Cogan 1977; Saio et al. 1977; Henden and Cox 1976; Cox et al. 1977; Deupree 1977c) and (2) (Deupree 1978) are considered unacceptable; mechanism (4) (J. Cox 1980) has not been followed up. This leaves us with (3) and (5).

It has been shown in a series of papers by A. Cox and collaborators (references in A. Cox 1980) that helium enrichment of the outer layers decreases the mass concentration of the star, and so can lower both Π_2/Π_0 and Π_1/Π_0.

This assumption of helium enrichment apparently resolves the beat (and possibly also the bump) mass discrepancy. However, this assumption itself creates other serious problems. For example, Cox et al. 1978) have postulated the existence of a "Cepheid wind" that is hydrogen-rich and that therefore leaves the helium behind, thus enriching the outer layers in helium. However, Sonneborn et al. (1979) and Kemp and Deupree (1979) have shown that any enhancement of helium in the atmosphere would not be easily observable in the emergent spectrum. (However, according to Takeuti 1979, the convection in the outer stellar layers ought with helium enhancement to be much stronger than previously thought; this increased strength might produce the Hα emission that has been observed [Barrell 1978] for some beat Cepheids.)

On the other hand, recent evidence by Luck and Lambert (1980) indeed suggests helium enrichment in the outer layers of Cepheids. However, this helium enrichment is throughout, say, the outer half or more of the stellar radius; and does not supply the μ-gradient needed in the ideas of A. Cox and collaborators.

The proposal by Stothers (1979b) that a small scale, tangled magnetic field might supply part of the pressure in the envelope also seems to resolve the beat (and possibly bump) mass anomaly. As shown by Stothers (1979b), field strengths in the stellar envelope of only $\sim 10^4$ G or less are required to reduce Π_1/Π_0 and Π_2/Π_0 sufficiently.

The tangled magnetic field proposal also removes the objection raised by Cogan (1978), regarding the slope of the curve on a Π_1/Π_0-Π_0 plot. However, it has subsequently been shown by Cox et al. (1979) that a sufficiently deep helium-enriched outer layer will remove the above slope discrepancy. It should be noted that the radiative models of Stothers (1979b) with the evolutionary masses and a tangled magnetic field with a large enough magnetic field strength are also in fair agreement with observations.

The fact that at least one Cepheid (W Sgr, Weiss and Wood 1975; Wood et al. 1977) has an observable magnetic field lends some credence to Stothers' idea. Such a tangled magnetic field may have originated in the collapse phase of the star-formation process, as discussed by Layzer et al. (1979) (see also Layzer 1965).

Finally, this reviewer would like to emphasize that the idea of the bumps being caused by a resonance effect leaves a number of questions unanswered and some puzzling facts unexplained. For example, Pel (1980) has stated that bumps exist (and are often very pronounced) even in the longer period Cepheids, with periods in the approximate range 17^d - 30^d (he cites some specific examples). Is the resonance idea borne out in these longer period Cepheids?

3.4. The Beat Cepheids

The "Cepheid mass anomaly" is most severe in the beat Cepheids: $M_{beat} \sim (1/4-1/2)M_{evol}$. It is becoming increasingly evident that these beat masses most likely have normal evolutionary values. This conclusion derives mostly from the recent work on beat Cepheids by Balona and Stobie (1979), Stobie and Balona (1979), and Niva and Schmidt (1979). Therefore it is important to know why pulsation theory is apparently giving us incorrect masses and radii for the beat Cepheids. This mass discrepancy will probably eventually lead (or perhaps has already led) to new knowledge about the beat Cepheids or about Cepheids in general.

On the other hand, the result of Stothers (1979b) could be looked at as follows. The required magnetic field strength is small enough that it may be forever unobservable (at least directly). As Stothers has pointed out, pulsation and evolution theory give pretty good results if the magnetic field is ignored altogether. Therefore, we may interpret Stother's results as saying that M_{bump} and M_{beat} are in about as good agreement with M_{evol} as we can expect without a great deal more theoretical work.

4. OTHER RECENT RESULTS

Among the other recent results, those connected with duplicity among Cepheids are interesting. According to Pel (1980), some 25% of all Cepheids are members of binary systems. The percentages given by Madore (1977) are consistent with those of Pel, as are those given by Madore and Fernie (1980).

One possibility is the case of SU Cyg, studied recently by Fernie (1979a). Its companion is a main sequence star of spectral type B6V. Another binary is the beat Cepheid TU Cas. Its companion is a main sequence star of spectral type A1.5V (Niva and Schmidt 1979).

A very interesting recent result, obtained by Mariska et al. (1980a), is that η Aquilae is a binary. The companion is thought to be a main sequence star of spectral type A0.5. Similarly, the Cepheid T Mon has been found to be a binary (Mariska et al. 1980b). The companion is probably a main sequence star of spectral type about A0.

It is of some interest to note that a secular period change has been detected in the 5.3-day Cepheid δ Cephei by Parsons (1980). He finds that the period of this star is decreasing at the rate of $d\Pi/dt = (d\Pi/\Pi)/(dt/\Pi) \approx -3.2 \times 10^{-9}$. A secularly decreasing period has also been reported for the 45-day Cepheid SV Vulpeculae by Fernie (1979b). He finds that the period of this star is also decreasing, at the rate of $d\Pi/dt \approx -8.1 \times 10^{-6}$.

5. SUMMARY AND CONCLUSIONS

We have reviewed some of the recent work on Cepheid (and Cepheid-like) variables. Most of this work centers around what this reviewer perceives as perhaps the three outstanding problems in Cepheid theory. These problems have not been solved, but significant steps in all of them have been taken.

In the area of the large amplitude mode behavior, true double-mode behavior has not yet been achieved with initial-value type nonlinear calculations. But we have the beginnings of a promising-looking theory of modal selection, pioneered mostly by Simon.

In the area of convection, we now have theoretical red edges of instability regions, thanks to the work of Deupree on the basis of nonlinear theory, and of Baker, Gough, Gonczi, and Osaki on the basis of linear theory. However, we still do not have a good understanding of convection.

Perhaps the most exciting developments have occurred in the area of Cepheid masses. Thanks in large part ultimately to the beautiful observation work by Pel, Hanson, Dean, Warren, Cousins, and Balona (and perhaps others), part of the "Cepheid mass anomaly" has disappeared. Because Cepheids are now thought to be somewhat redder and more luminous than previously believed, the "pulsation mass" is now in satisfactory agreement with evolution masses. The "Wesselink mass" is also fairly satisfactory. Thus now only the "bump mass" and the "beat mass" are perhaps anomalous with regard to evolution theory.

Thanks to the theoretical work of Deupree, Cogan, A. Cox, and Stothers (and perhaps others), we now have possible resolutions of even these remaining mass discrepancies. We feel that these discrepancies will eventually lead (and may already have led) to new knowledge about Cepheids. For example, the work of A. Cox and collaborators on helium enrichment in the outer layers of Cepheids may have revealed the existence of inhomogeneities in composition, caused perhaps by "Cepheid winds." Also, the work by Stothers on tangled magnetic fields in the outer layers of Cepheids has shown that even a moderately weak magnetic field, maybe too weak for direct detection, is sufficient to resolve the beat (and possibly also the bump) mass anomaly. Perhaps more interesting, this work has shown that the beat (and possibly also bump) masses may be in about as good agreement with evolution theory as we can expect without a great deal more theoretical effort.

The work by Fernie, Madore, and Mariska (and perhaps others) on duplicity among Cepheids may eventually lead to direct mass determinations for some Cepheids.

Finally, the reported period changes in δ Cephei and in SW Vulpeculae by Parsons and Fernie may provide a check on theories of stellar evolution.

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DISCUSSION

SIMON: Neither Richard is here today. In the solutions to the bump mass discrepancy you left out the Carson opacities. I am not particularly partial to the Carson opacities, but I would like to say a word in favor of that solution at the moment. In work that I did just before coming here, comparing observations and theory I found that the use of the Carson opacities significantly ameliorates the bump mass problem. The 10 day Cepheids are matched by models at 14 days instead of 19 or 20 days which is what you get with evolutionary masses using Los Alamos opacities. If you were to take Carson opacities and reduce the mass a moderate amount, say 15 or 20% you would solve the bump mass discrepancy. This doesn't work for the beat masses. I don't know whether the Carson opacities are right or not and I don't want to get into that. I don't know anything about the calculation of opacities, however, I would like to say that you do get significant amelioration of the problem if you use the Carson opacities.

MOFFET: By tangled magnetic fields do you mean fields similar to magnetic fields associated with sunspots?

J. COX: I suppose that might be the scale, much less than a stellar radius.

A. COX: I guess I would like to make a few remarks. There is a paper out. I don't know if Tom Barnes is here or not, but he gave me a preprint of a paper by David Lambert, who has looked at the products of the CNO cycle and he finds a lot of nitrogen enrichment in the atmospheres of Cepheids, which is probably just a dredge up during the red giant stage, but he does imply that the helium is very abundant in Cepheids. The thing I don't like about it is that I want a gradient, lots of helium at the top and none at the bottom and he gets it throughout.

BARNES: Maybe I could expand on that a little bit. I don't have any connection with the work, but I got the paper from Lambert. In a program investigating CNO abundances in supergiant atmospheres, including Cepheids, he is looking for dredge up of CN processed material. He found that the C abundances are depleted. The nitrogen abundances are up as expected. He finds a substantial oxygen deficiency and far too much nitrogen excess. The sum of the CNO abundances come out right, but nitrogen is way too high for CN processing and the oxygen is down. He argues that you can get that effect by having oxygen-nitrogen processing with dredge up of that material and if you have the oxygen-nitrogen processing, you make a lot of helium and you would dredge that up as well. If he uses that argument and matches the abundances he finds envelope helium abundances ranging from $Y = 0.4$ up to $Y = 0.8$. The interesting thing is that one has the most pronounced helium abundance in TU Cas. As Art said, the problem is that it just uniformly makes the star all helium. It doesn't give you a gradient.

COGAN: I would comment that of course that would create problems with regard to the blue edge. It will move the theoretical blue edge further away from the observed blue edge.