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V. STELLAR PULSATIONS AND STABILITY; SHOCK WAVES AND NON-STATIONARY PROCESSES IN STARS

Some aspects of the current interpretation of Cepheids have been reviewed by Ledoux and Whitney (1) and Zhevakin (2) has written a clear and up-to-date account of the pulsation theory of variable stars. The latter has continued his investigations (3) on stellar variability due to the vibrational instability arising, mainly in the second ionization zone of helium assumed in radiative equilibrium, on account of the reduction of the Γ's (and consequently of the temperature variations) and the behaviour of the opacity there. On the basis of the linear nonadiabatic pulsations of his 'discrete' models, Zhevakin has discussed in great detail the phase-shift between the radiation flux and the radial velocities and the factors that affect it in view of explaining the peculiarities of this phase-shift in different types of variable stars.

The de-stabilizing influence of the second helium ionization for stars in the general vicinity of the Cepheids strip has been confirmed by the detailed investigations of Baker and Kippenhahn (4) and J. P. Cox (5) provided that the main transfer of heat there be by radiation and not by convection as detailed investigations seem indeed to indicate.

As to the exact location of the zone of maximum (linear) instability in the H-R diagram one might expect on general ground that it should coincide rather exactly with the actual Cepheid strip providing, at the same time, an explanation of the Period-Luminosity relation. Detailed computations (6) however seem to show that it is shifted to the right by about 600° in effective temperature.

As far as the phase-shift is concerned, Baker and Kippenhahn, contrarily to Zhevakin, failed to recover the observed 90°-value. In this respect there is no absolute necessity to reach an interpretation in the frame of this theory and explanations in terms of linear and non-linear mechanisms outside of it have been proposed at different times, the latest one, resorting to a periodic alternance of radiative and convective equilibria in the ionization zones, being due to E. Böhm-Vitense (**7**). However, it is also possible that the approximate pressure boundary condition used by Baker and Kippenhahn which forces a peculiar behaviour of the pressure variation close to the surface, is partly responsible for the discrepancy.

All these investigations were perforce limited to the external part of the star since no reasonable models were available for Cepheids. However, with the recent progress in evolutionary tracks for fairly heavy stars, the situation should improve rapidly in that respect. On the other hand, despite the many attractive features of Zhevakin's theory especially as far as providing also a natural mechanism for the limitation of the amplitude to some finite value, the present reviewer (cf. **1**) still feels uneasy about the rôle of the higher modes which, on the basis of any theory situating the source of instability far out in the external layers, should also be excited at least as strongly as the fundamental one.

An interesting analysis especially of the possible effects of convection on stellar pulsations is due to R. F. Christy (**8**) who, since then, has tackled numerically and with encouraging results, the non-linear problem (**9**) looking for stationary periodic solutions of the general equations of motion in external stellar envelopes of stars of the RR Lyrae type and susceptible to represent their observed finite oscillations. This is, in some respects, quite a formidable problem but perhaps the use of large computers will indeed bring us to the solution much more rapidly than expected although some measure of caution is still indicated. Anyway, work on this problem is also reported by A. N. Cox and K. H. Olsen (**10**), by J. P. Cox, A. N. Cox and K. H. Olsen (**11**) as well as by V. I. Aleshin (**12**), all with some measure of success either in following the establishment of finite self-excited oscillations or (and) in recovering observed characteristics of the light and velocity curves.

As far as RR Lyrae and β Canis Majoris stars are concerned, theoretical work is going on in Oslo and a general critical review of the problems raised by the first group of stars is in preparation by E. Haugen (**13**). On the other hand, in the course of their general work on the stability and the oscillations of rotating gaseous masses (**14**), Chandrasekhar and Lebovitz have encountered a possibility of a coupling between two normal modes for a value of Γ_1 of the order of 1·6 which has led them to a new suggestion (**15**) as to the interpretation of the double periods in β Canis Majoris stars.

Accounts of the present state of the linear theory of stellar stability have been prepared by P. Ledoux (**16, 17**) using for the presentation of the general problem a point of view related to that adopted by Jeans in '*Astronomy and Cosmogony*'. Special attention has been paid to the effects of nuclear processes in particular nuclear equilibrium and, in (**17**), on the significance of stability considerations for stellar evolution. The remark is also made that the general problem is fundamentally of a higher order in the time than suggested by the usual treatment and that time-scales other than those associated with the classical subdivision into dynamical, vibrational and secular stability might be significant. In fact, in some independent unpublished work by A. S. Thompson (**18**), an effect of that type is discussed explicitly although partially and perhaps not quite adequately.

Boury (**19**) has studied the vibrational stability of initially pure hydrogen stars taking into account the thermo-nuclear reactions between elements formed during the contracting phases and has determined the critical mass ($M_c \simeq 300\ M_\odot$) above which they become unstable. The effects on vibrational stability of convective energy transport and turbulent viscosity in the extensive cores of massive main sequence stars has been investigated in detail by Boury, Gabriel and Ledoux (20) who find that they affect very little the value of the critical mass derived by Schwarzschild and Härm. On the other hand, Gabriel (21) has shown that the current wholly convective models used to represent small mass stars at the lower end of the main sequence are vibrationally unstable.

The general fourth order problem for the non-radial oscillations of the main sequence models of Schwarzschild and Härm has been solved for a series of modes and spherical harmonics of different degrees by P. Smeyers (22) who is carrying on a discussion of the interaction, through the g-modes, of convective and dynamical stability and also of the vibrational stability of the models.

P. Ledoux has started a general investigation of the asymptotic behaviour of very high modes of radial pulsation (23) which show that the amplitude becomes negligibly small everywhere except close to the centre and in the external layers. This suggests the possibility of a special type of close interaction between these regions which is being checked by a study of the vibrational stability of these high modes. This discussion is being extended to the asymptotic non-radial modes.

Secular stability whose discussion is the least advanced and which is perhaps in need of a new start has been apparently the object of little research, and the only paper of which I am aware is due to Y. Osaki (24) who has developed a criterion of secular stability for degenerate stars on the basis of the relation between the variations of entropy and temperature.

It is impossible to review here the extensive work of Chandrasekhar and Lebovitz on the stability of rotating fluid configurations using high order virials. Among the papers which have appeared in the *Astrophysical Journal* these last three years, we have already referred to a few (14) and (15) which are of special interest for this Commission and we may add another one by Chandrasekhar and Lebovitz (25) devoted to the interaction between dynamical and convective instability in gaseous stars and one by Chandrasekhar (26) concerning a general variational principle applicable to both radial and non-radial oscillations of compressible masses.

Applications of the generalized virial to the hydromagnetic oscillations of a self-gravitating fluid have been developed by D. G. Wentzel (27) and Woltjer (28) has emphasized the point that for non-radial oscillations of reasonable configurations the direct effect of the presence of a magnetic field is to increase the frequency, thus to reinforce the stability. Kristian (29) has studied the hydromagnetic oscillations of a fluid sphere about a stationary (non-static) state. In presence of a small field H, he finds modes with frequencies directly proportional to H as well as the more usual ones whose frequencies are corrected by a term proportional to H^2.

Considerable developments are to be noted in the application of the theory of shock waves to stars mainly to explain either peculiarities in the spectrum of variable stars or the characteristics of novae and super-novae. With respect to the latter a general review by Schatzman (30) should appear shortly which contains some new suggestions concerning the increase of radius of novae during the exploding phase and the mechanism of mass ejection.

Many of the detailed investigations rest on extensions of Chisnell's and Whitham's methods to stellar configurations. Ono and Sakashita (31) have discussed super-novae explosions, considering that the gravitational energy released by the collapse of the core of a far evolved star and by the nuclear reactions induced in the envelope generates a shock. The propagation of the latter through the envelope can then be followed using their previous results giving, in a physical star, the rate of variation of the strength of the shock and the material velocity behind it as a function of the distribution of the state variables in front of it. This allows one to compute the point where the material velocity reaches the escape velocity and the mass above it which is ejected. Again Ohyana (32) using the same general picture but including more explicitly the energy released by reactions between light elements such as C and O following the collapse of the core and the effects of the escape of radiation from the shock as it approaches the stellar surface finds general agreement with the observational data of type II super-novae. Another variant of this is used by Sakashita and Tanaka (**33**) in an attempt to relate the origin of Planetary Nebulae to the helium flash in red giants.

The propagation of strong shock waves in polytropic gaseous spheres has also been studied by Nadezhin and Frank-Kamenetski (**34**) who discussed the fraction ΔM of the mass loss in term of the initial energy E of the disturbance ($E \simeq GM^2/R$, $\Delta M \cong M$; $E = 10^{-3}\, GM^2/R$, $\Delta M \cong 10^{-6} M$). On this picture, taking radiation and the ionization of hydrogen in the external layers into account, Imshenik and Nadezhin (**35**) have constructed theoretical light curves of novae and super-novae in reasonable agreement with the observations.

Colgate and his group (**36a**) have continued to work on the problem using a more direct numerical approach but they seem to have had difficulties in making the collapsing configuration bounce back especially if the emission of neutrinos is taken into account. However a non-negligible interaction of the envelope with the flux of neutrinos has been suggested as a possible way out (**36b**). Using his work reported in Sect. IV, Emin-Zade (**37**) assumes that, before outbursts, novae are white-dwarfs containing a residual abundance of hydrogen of several percents, the explosions being attributed to the strong increase of the rate of thermonuclear reactions due to expansion and transition from a condensed state to normal stellar plasma.

In two papers (**38**), Masani, relying especially on Witham's method, gives approximate formulae and tables for the evolution of the strength of a weak adiabatic shock as it propagates in a spherical compressible mass and which bring out the different behaviour in the central regions where the curvature effect is dominant and the external half where the gradient of density is the main factor. Kaplan (**39**) has also investigated the propagation of ordinary and shock waves in stellar interiors and envelopes paying special attention to the transformation of Riemann waves into shock waves.

With a view to applications to surface nuclear reactions and the explanation of peculiar abundances, Schatzman (**40**) has discussed the accelerations of particles in a magneto hydrodynamic shock in presence of heterogeneities in the magnetic field.

The effects of precursor radiation in the Lyman continuum on the structure of a shock front in a stellar atmosphere have been studied by Whitney and Skalafuris (**41**). The general effects of radiation and conductivity on shock waves have also been discussed by V. S. Imshenik (**42**). Frank-Kamenetski (**43**) has investigated radiative transfer of energy in the continuum in a medium which is not in thermal equilibrium and Kaplan (**44**) has considered the scattering of light in a non-stationary medium. I. A. Klimishin (**45**) has also discussed the influence of emission and absorption of energy on the characteristics of a shock wave moving in a stellar envelope. He has analyzed (**46**) the possibility for a medium shock wave to throw off an external envelope in a giant star and has discussed the possibility of stationary supersonic ouflow of material from stellar atmospheres (**47**). Attention may also be drawn to the general discussion on shock-waves in stellar envelopes and their astrophysical implications in the Proceedings of the Varenna Symposium on aerodynamic phenomena in stellar atmospheres (**48**).

The same volume contains also a chapter on non-catastrophic mass-loss from stars with a very elegant presentation of the relevant fundamental hydrodynamics by Germain.

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