35. COMMISSION DE LA CONSTITUTION DES ETOILES

Report of Meetings, 26 and 28 August 1964

PRESIDENT: M. Schwarzschild.

ACTING PRESIDENT: P. Ledoux.

SECRETARIES: M. H. Wrubel, G. Ruben.

Three meetings were held, part of the first meeting being devoted to administrative matters.

A. Administrative matters

(1) M. Schwarzschild expressed his regret that other duties prevented him from being able to compile the Draft Report and his appreciation to P. Ledoux for undertaking this responsibility and organizing the scientific sessions of the present meeting. He then asked P. Ledoux to preside this meeting as temporary President of Commission 35.

The latter expressed his warmest thanks to all the members of the Commission for their cooperation in the preparation of the Draft Report. Special thanks were due to Mrs Massevitch and Dr Hitotuyanagi for summaries of the work accomplished during the last three years in their respective countries.

(2) The Draft Report was then open for discussion. Schwarzschild moved that the Draft Report be accepted with the understanding that the President would be allowed to make minor corrections and/or additions as necessary. It was requested that suggestions for such additions or corrections by members be transmitted to the President in writing.

(3) The President noted that Dr Massevitch was unable to attend this meeting and a message was sent to her expressing regret and thanking her for the help she has given this Commission on many occasions.

(4) Schwarzschild recalled that opacities are available in two forms—as computer codes which can be run when needed and as published results. It was his strong opinion supported by the Commission that results, such as are being obtained by A. N. Cox and others, be published as extensively as possible. The President stated that he had received a letter from A. N. Cox giving detailed plans for such a publication of his results in the near future.

(5) The President noted a request by Commission 36 that effective temperature be designated T_{eff} and that T_{e} be reserved for electron temperature.

B. Scientific Sessions

1. *Opacities*

T. R. Carson described an opacity programme being developed at St. Andrews in collaboration with D. W. N. Stibbs and D. F. Mayers. The generalized temperature dependent Thomas-Fermi statistical model of the atom is used and the cross-sections computed from the numerical solution of Schrödinger's wave equation using the electric potential and associated electron density in the neighbourhood of an atomic nucleus derived from the appropriate Poisson equation. Scattering and various mechanisms of line broadening are taken into account. In its present form, the programme, which is coded for and is running on an IBM 7094 II, can handle a mixture of up to twenty elements with a total of 4000 edge or line components.

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In response to a question, *Ruben* said that there was no extensive work on opacities now going on in the U.S.S.R.

A. N. Cox was not present at this session and there was no report on recent Los Alamos work but, later on, he renewed his offer to run opacity programmes for particular chemical compositions to help anyone engaged in problems of stellar structure and stellar evolution.

2. *Ages of old star clusters*

R. L. Sears reported calculations of the early stages of evolution away from the main sequence. These differ from the earlier work of Hoyle both in the assumed chemical composition and in the inclusion of more precise opacities and expressions for energy generation. The best fit for M 67 required an age of $4 \cdot 2 \times 10^9$ years with the assumed composition $X = 0 \cdot 73$, $Y = 0 \cdot 25$, $Z = 0 \cdot 02$. A gap is predicted in the number of stars just below the turn off and this has recently been observed by Sandage and Eggen although the theoretical gap is somewhat lower than is observed. A similar approach gives for NGC 188 an age of 9×10^9 years.

Tracks for globular clusters agree in shape with Hoyle's older work but do not agree well with observations. The ages of the globular clusters therefore remain very uncertain.

A. Weigert commented on the possible effect of the difference between the local pressure scale height and the non-local density scale-height which might be important in the redgiant region.

W. Fowler noted that there is evidence for an additional increase of 3% in the rate of the proton-proton chain, giving a total of 13% over the 1957 value.

P. Demarque commented that, with the same composition as Hoyle had used but more precise values for the opacity and energy generation, he has obtained significantly different answers.

Öpik suggested that agreement with observations could be achieved by starting with a stratified model containing more heavy elements in the core. But Cameron pointed out that if Hayashi is right, this would not be justified.

3. *General work on stellar evolution, especially of fairly massive stars*

Kippenhahn reported the recent results of the Munich group using the Henyey method together with Cox opacities for a mixture of extreme Population I : $X = 0 \cdot 60$, $Z = 0 \cdot 044$. Results were described for $1 \cdot 5$ and $7\,M_{\odot}$. The models for $1\,M_{\odot}$ have been followed from the Hayashi track to the main sequence and then almost as far as the helium flash.

The first models for $7\,M_{\odot}$ have now been corrected for the effects of lines opacity but only minor changes are noted.

The results were presented in a series of diagrams illustrating especially the multiple crossings of the Cepheid region by the model as it evolves back and forth across it. It was noted in particular that during the stages of evolution when a helium burning shell is moving outwards in the star, an outer convection zone brings envelope hydrogen inwards to a region of high temperature. At about the same time as carbon burning begins in the core, hydrogen burning begins in this outer layer. There does not appear to be a mixing of zones; the hydrogen does not penetrate in the carbon region.

Neutrino emission was not included. *Reeves* recalled that Hayashi finds that neutrinos eliminate the carbon flash.

Ruben reported on work in progress in the U.S.S.R. bearing on the various mathematical methods in use to compute sequences of evolution and their mutual agreement. Main sequence models and early evolution, neutrino emission (especially Mrs Massevitch and her group), shock waves, pulsation and rotation are also being investigated.

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Neutrino luminosity on the main sequence is less than photon luminosity by five to six powers of ten. For giants and supergiants of ten times the solar mass and of spectral type M, neutrino luminosity can reach 10% of the photon luminosity through the reaction

$$\gamma + e^- \rightarrow e^- + \nu + \bar{\nu}$$

The same relative importance of the neutrino losses may be attained in stars more massive than 50 $M_\odot$ taking into account the reaction

$$\gamma + \gamma \rightarrow \nu + \bar{\nu}$$

Population II stars of our Galaxy (M $\simeq$ 1) and white dwarfs have a neutrino luminosity less than 1% of the photon luminosity.

Preliminary results for main sequence stars of 2, 4, 8 and 16 $M_\odot$ show that the dependence of log L, log R, log P and log T on hydrogen content is approximately linear. However the exact relation of the theoretical results to observational quantities remain a difficult problem.

Kippenhahn pointed out that the speed of evolution depends only on the core so that local neutrino loss is important. *Fowler* emphasized that, with recently suggested modifications, the Gamow Urca-process, which does not require the universal Fermi interaction, may prove to be important. *Schwarzschild* asked if the neutrino luminosity ever exceeds the photon luminosity during the α-process and *Iben* replied that for 15 $M_\odot$, when the star is mostly carbon and oxygen, the neutrino luminosity becomes large.

Iben reported computations of tracks from the Hayashi contraction through the hydrogen and helium burning for masses ranging from 0·5 $M_\odot$ to 15 $M_\odot$. The individual isotopes important in the nuclear reactions were explicitly followed at all times. Above 1·25 $M_\odot$, there is a double maximum in luminosity before reaching the standard main-sequence. The first is due to the onset of the conversion of C^{12} to N^{14}. At 15 $M_\odot$, helium burning takes place as the star is crossing the colour-magnitude diagram from left to right. During the red giant phase, the convective envelope penetrates to the region where nuclear reactions have processed the material and the nitrogen to carbon ratio is changed by a factor of three. This might be observable.

Schwarzschild noted that mass loss should be kept in mind. *Cowling* mentioned the possibility that minor explosions in the centre of the star might provoke mass loss on the surface.

4. *Formation of helium and the radioactive elements*

Cameron described recent efforts to account for the large amount of helium in the galaxy. Calculations were described for a model in which stars were formed according to the Salpeter function and the remnants are stars of the average mass of white dwarfs. The resulting abundances of hydrogen, helium and the radioactive elements were given as a function of time. In particular, it appears that massive stars, having only a small amount of helium between the hydrogen burning shell and the interior already converted into heavier elements, are much less efficient in producing helium than is usually assumed. On the other hand, the abundance ratios of the radioactive isotopes vary so little over long periods that we do not get much information about age from them.

Bondi noted that prestellar helium may indicate a very dense state during the early stage of the universe. *Tayler* reported that he and Hoyle had recomputed the helium production in a Gamow universe and found it greater than observed.

Schwarzschild pointed out that, since the mass-luminosity relation is sensitive to the mean molecular weight, observations of an old double star would bring extremely valuable information in that respect.

5. *Observational neutrino astronomy*

Bahcall described two neutrino experiments that may be carried out by Davis and by Reines during 1965. The most likely source of observable neutrinos is the Sun where the rare B^8 branch of the *p–p* chain produces 90% of the observable neutrinos. The predicted ratio of counts to background is 20. Cosmic ray secondaries may also be observed and, if recent hypotheses are correct so might strong radio-sources. Eventually, it might be possible to do neutrino spectroscopy.

6. *Extremely massive stars*

Fowler led a discussion on very massive stars and presented a few of the details of his approach which could not be discussed during the earlier joint discussion on radio sources.

7. *Incipient vibrational instability along the evolutionary paths of fairly massive stars*

Baker gave the results of the linear non-adiabatic radial pulsation analysis of the models of 5 $M_\odot$ and 7 $M_\odot$ computed by Hofmeister, Kippenhahn and Weigert. It was presumed that convection in the surface layers was not influenced by the pulsation so that only the interaction between the radiation-field and the pulsation had to be considered taking into account as realistic opacities as possible and the ionization of H and He. This leads to vibrational instability for all models lying in the region of the Cepheids whether they cross it one way or the other.

The periods of the fundamental mode of radial pulsation (provided by a programme written by Temesvary for the models as they cross the Cepheid gap) are quite sensitive to the mass and the depth of the hydrogen-convection zone but very little to changes of about 10% in the hydrogen content and 30% in the metal content.

The values of the period along the line of maximum vibrational instability yield a theoretical period-luminosity relation which is in reasonable agreement with the observed relation. On crossing the Cepheid gap, models of a given mass exhibit both increases and decreases of the period depending on the direction of the crossing which is rather suggestive of the observed changes.

Schwarzschild emphasized the importance of this aspect of the problem as it provides a new check on the theory.

8. *Non-linear oscillations and applications to intrinsic variable stars*

Christy presented some of his results on non-linear oscillations for RR Lyrae stars models. Five sequence were calculated for 0·38 $M_\odot$ and one for 0·88 $M_\odot$. The helium content of the 0·38 $M_\odot$-models ranged from 0·00 to 0·60. Surface condition was $P = 0$ and the lower boundary was at 10^6°K. It appears that solutions of the complete non-linear equations stabilize fairly rapidly to some finite amplitude in the cases considered giving quite realistic light and velocity curves. Sometimes, the solution corresponds to the fundamental mode of linear oscillation sometimes to the first harmonic which seems to be definitely lacking if the helium content is appreciably smaller than 0·45.

The shape of the curves is sensitive to T_{eff} and secondary humps associated with the underlying ionization transitions appear in some cases.

J. P. Cox reported on somewhat similar work carried out at the Los Alamos Scientific Laboratory for $M = 5{\cdot}4\ M_\odot$ and two chemical compositions [(1) (He/H) by numbers = 0·15, $Z = 0$; (2) (He/H) by numbers = 0·16 and $Z = 0{\cdot}02$] in view of applications to the classical Cepheids. In this case, the envelope extends only to about $T \simeq 10^5$°K which is a disadvantage

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as far as the periods are concerned as they come out too small by a factor of order 2. Emphasis has been put on the study of the growth or damping of the initial perturbation and on the relation of this to the exciting mechanisms revealed by the linear theory, confirming in particular the destabilizing influence of the second helium ionization. In cases of instability, which were found for both chemical compositions, the motion, after a considerable number of periods, became strictly periodic at a finite but fairly small amplitude. The stability of this finite periodic motion has been tested by superposing a new perturbation which soon vanishes.

The strip of instability in the H–R diagram shows reasonable agreement with the Cepheid band but the effects of the ionization of hydrogen would have to be taken into account in more details.

9. *Models of rapidly rotating stars*

R. A. James described very briefly his work in which characteristics of rotating polytropic (n = 1, 1·5, 2, 2·5, 3) and degenerate (y_c^{-2} = 0·025, 0·05, 0·1, 0·2, 0·4, 0·6, 0·8) configurations were obtained by using Taylor-series for quite a range of $A = \omega^2/8\pi G\rho_c$ or $\omega^2/8\pi G y_c^2$.

Roxburgh reported some of the results obtained for fast rotating stars, assuming that nearly all the mass is in a central core which is little affected by the rotation. The main difficulties arise from the surface boundary conditions which are not known for rotating stars and from the intricate influence of rotation on convective layers. The differential equations in the outer parts are solved for a polytropic gas. The case of radiative equilibrium is much more difficult to solve.

Comparison with observation is difficult as in this case the usual definition of the effective temperature fails. The following table compares the results for a rotating star (P : pole-on; E : equator-on) with those of a normal star (asterisk):

$L = 0{\cdot}7\, L^*$
$R_P = 0{\cdot}9\, R^*$, $R_E = 1{\cdot}35\, R^*$
$T_P = 0{\cdot}87\, T^*$, $T_E = 0{\cdot}80\, T^*$

Schwarzschild expressed his satisfaction at the great progress made in the theory of pulsation and rotation since the last meeting of the IAU.

Bondi suggested that, in rotating stars, the effective temperature should be calculated not for the whole visible surface but only for the central parts of the different possible visible disks.

Deutsch mentioned that such differences between pole-on and equator-on characteristics seem to have been observed by Kraft.