REMARKS ON THE COMPUTATION OF EVOLUTIONARY TRACKS

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This communication will be very short, because the computing program with which it is concerned fell about two months behind schedule. The program consists in setting up the problem of stellar evolution for an automatic digital computer in such a way that, given the starting composition and the mass of a star, the machine proceeds to work out the evolution with time without any human intervention being necessary.

It was recognized when the program for this conference was being drawn up that to get everything working in a satisfactory way, and to make computations to an advanced stage in the evolution of Type II stars, would be a race against time. In the event the race was lost, I am sorry to report. The satisfactory working of the machine in any complete sense was only achieved about a fortnight ago; and this left much too little time for any extensive calculations to be made. In the short time at my disposal I decided to examine the early phases in the evolution of stars with masses in the range 1 $\mathfrak{M}_\odot$ to 1.4 $\mathfrak{M}_\odot$. This was done using the best present day rate for the C-N cycle. The reasons for this choice were twofold — that some results could be obtained in the time available, and that a determination of the early phases (on the H-R diagram) is crucial to the

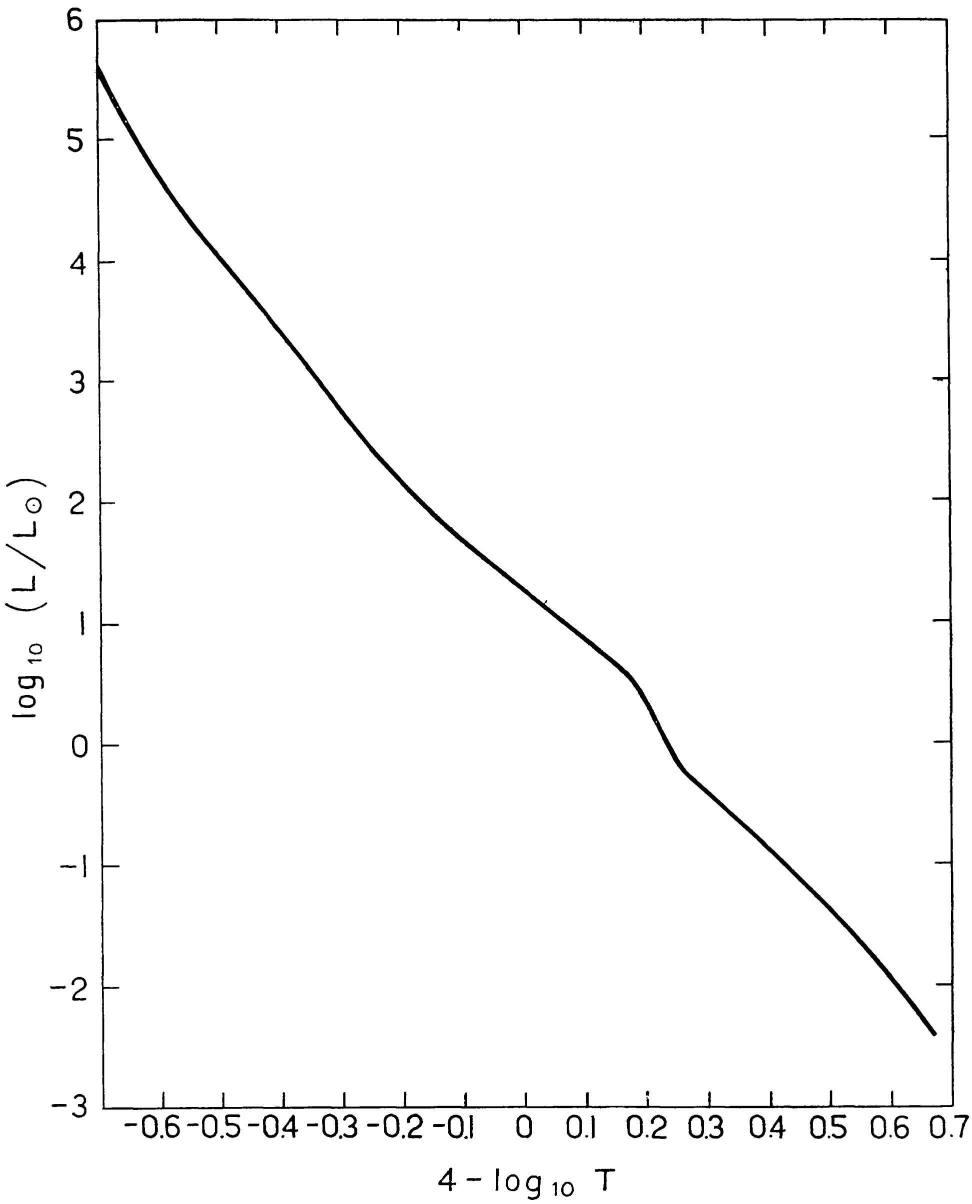

FIG. 1 — Calculated change in bolometric luminosity L (in terms of solar luminosity with effective temperature T, for main sequence stars of Type I ($Z \sim 0.02$). The mass of a star at the low luminosity end of the curve is about $1/5\,\mathfrak{M}_\odot$

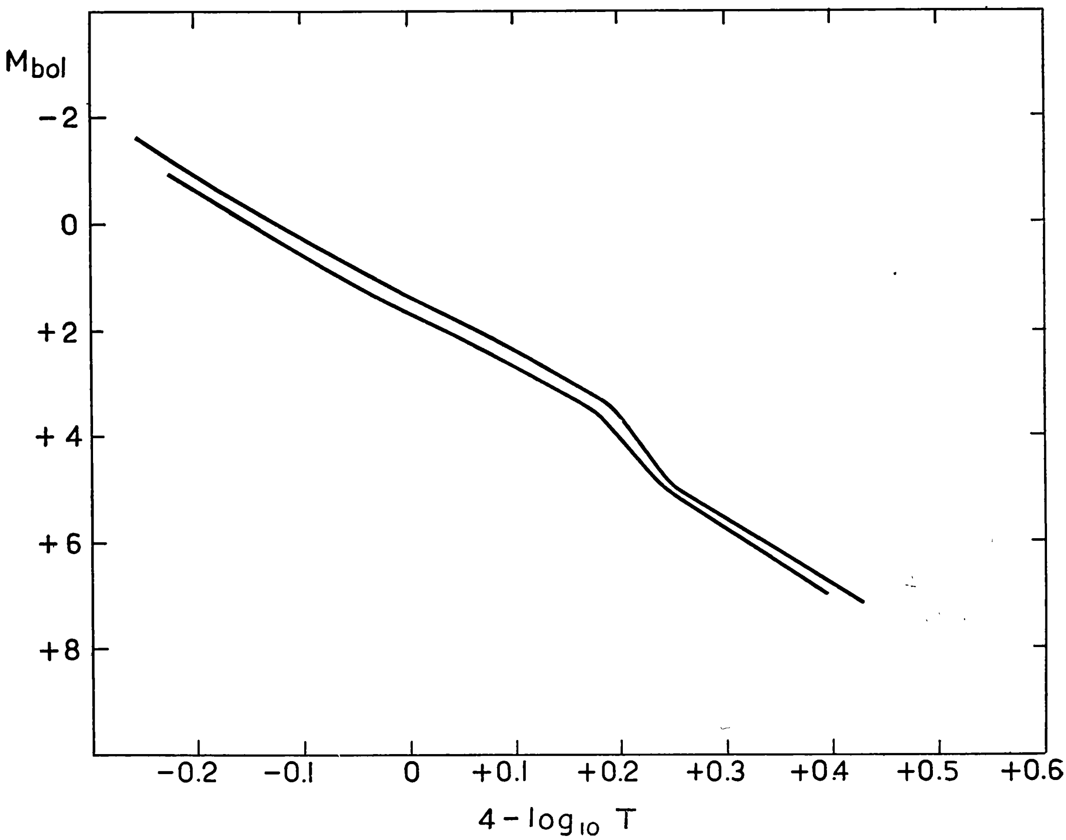

FIG. 2 — Calculated change in absolute bolometric magnitude M_{bol} with effective temperature T for two main sequences: Type I (composition of solar type) above; Type II (metal content and helium content reduced by a factor of 15) below.

estimation of the ages of Type II stars (as SANDAGE has explained in an early paper).

The Type II sequence was followed to approximately the second turning point, the calculations occupying a time of approximately 4 hours on the IBM 704. The calculated points agree well with the observed sequence, and do not show the rapid oscillation on the H-R diagram, as previously reported by HASELGROVE and HOYLE. This difference is almost certainly due to the decreased importance of the C-N cycle in the current calculations.

A rather disturbing feature of the new work is that the evolutionary track does not move immediately away from the main sequence. The track initially moves up the main sequence over a range of approximately 1.5 magnitudes before the "turn-off" point is reached. Most of the lifetime of the star is taken up by this early main sequence phase. This is awkward in the sense that the "turn-off" point no longer seems to give a good indication of age — so much time being spent below the "turn-off" point. This result, it must be emphasized, is very preliminary, and requires confirmation. The effect would be to revise age estimates in an upward direction — by how much it is still too early to say. It may be added that the new calculations treat the development of a burnt-out core in more detail than has been done before — or so I believe. The new result depends on this increased detail.

A similar calculation was performed for the Sun. It turns out that the Sun is following an evolutionary track similar to that just described. It is still moving upwards more or less parallel to the main sequence. After a rise of almost 2 magnitudes, from an initial M_{pv} near $+5{\cdot}0$ it will turn away from the main sequence and move rapidly to the right in the H-R diagram. The results justify a somewhat more detailed representation than is given by the H-R diagram. Thus in Figure 3 the behaviour of the solar luminosity L and radius R are plotted as a function of time. $L_\odot$ and $R_\odot$ refer to present day values. According to the figure the age of the Sun is a little greater than $1{\cdot}5 \times 10^{17}$ sec, i.e. about 5×10^9 years, in excellent agreement with current estimates of the age of the solar system. The figure shows that the Sun was initially about $0^{m}\!.5$ fainter than at present, in agreement with the recent estimate of SCHWARZSCHILD, HOWARD, and HÄRM. The future of the Sun is also clearly shown by the figure. Although the matter falls a little outside the terms of reference of the present conference, the future span available to life on the Earth can be seen to lie in

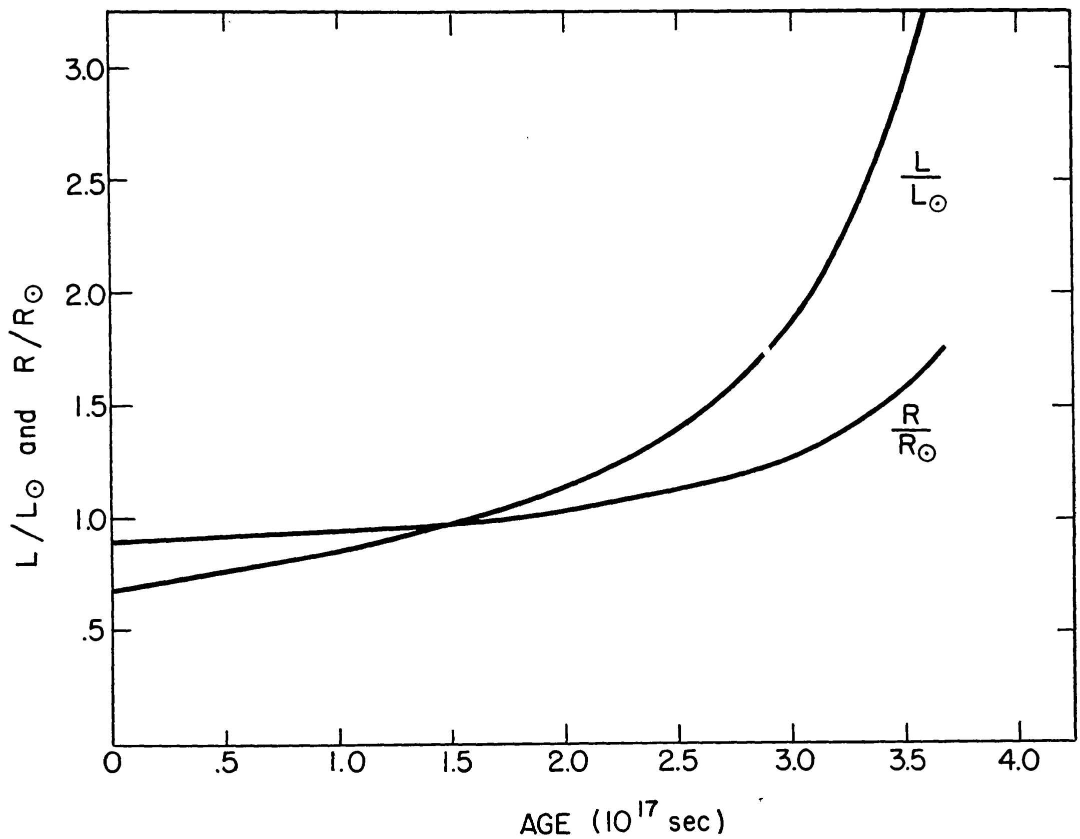

FIG. 3 — Behaviour of the luminosity, L, and radius, R, of the Sun as a function of time. $L_{\odot}$ and $R_{\odot}$ refer to present day values.

the region of 2-3 billion years – after a further 5 billion years the oceans will boil and no life will surely persist then.

I would just add that the results shown in Figure 3 were computed in a series of about 30 time steps, occupying the machine for about 2½ hours. The computations were entirely automatic. That is to say, once the machine was started up, there was no further human intervention.

DISCUSSION

CHAIRMAN: L. SPITZER

SALPETER

You said that the stars you calculated increased in luminosity by 1½ magnitudes before turning off the main sequence. Does this tally with KUSHWAHA's results?

HOYLE

His stars were more massive.

SALPETER

KUSHWAHA found that the increase became bigger at higher masses.

SCHWARZSCHILD

I would expect a smooth increase above 2.5 solar masses, but not in the interval 1 to 2.5.

SPITZER

What is the physical reason why a star remains initially on the main sequence for so long an interval?

HOYLE

A star stays near the main sequence if it is of uniform composition and in this respect the proton-proton reaction is much more uniform than the C-N cycle. I can't say anything about stars of high mass as I have not made any computations for them.

STRÖMGREN

Could you comment on the role of the convective zone? Does it play a different part in type I and type II stars?

HOYLE

It makes little difference so long as H supplies the free electrons. Even when the surface temperature falls sufficiently for the metals to provide the free electrons, a small change in surface temperature would have the same effect as a change in the contribution of the metals.

STRÖMGREN

I take it that the outer convective zone was included in these calculations.

HOYLE

Yes. I should point out that on the diagram showing the main sequence of type I and type II, adjacent positions of the two curves correspond to quite different masses.

SALPETER

What is the explanation of the wiggle on the calculated main sequence curves?

HOYLE

The development of a convective zone, the transition from the proton-proton to the C-N reaction and the changing opacity are all contributing. The method of computing leaves one almost helpless to disentangle those factors.

Sandage

There is a wiggle in the observed colour-magnitude diagrams about 2 magnitudes brighter than the Sun. The observed shape of the c-m diagram in this region is similar to those shown in Hoyle's computation but the kink occurs at a different absolute magnitude.

Hoyle

My variation is similar in form but about a magnitude fainter.