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AUTHOR(S): Michael J. Newman
Karl-Heinz A. Winkler

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los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87545

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THE PRE-MAIN SEQUENCE SUN:
A DYNAMIC APPROACH*

Michael J. Newman
Theoretical Division
Los Alamos Scientific Laboratory
University of California

and

Karl-Heinz A. Winkler
Max-Planck-Institut für Physik und Astrophysik
Munich, F.R. Germany
and
Theoretical Division
Los Alamos Scientific Laboratory
University of California

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ABSTRACT

The classical pre-main sequence evolutionary behavior found by Hayashi and his coworkers for the Sun depends crucially on the choice of initial conditions. The Hayashi picture results from beginning the calculation with an already centrally condensed highly Jeans unstable object not terribly far removed from the stellar state initially. In the present calculation we follow the work of Larson in investigating the hydrodynamic collapse and self-gravitational accretion of an initially uniform just Jeans unstable interstellar gas-dust cloud. The resulting picture for the early history of the Sun is quite different from that found by Hayashi. A rather small ($R \approx 2R_\odot$), low luminosity ($L \approx 30L_\odot$) protostellar core develops. A fully convective stellar core, characteristic of Hayashi's work, is not found during the accretion process, and can only develop, if at all, in the subsequent pre-main sequence Kelvin-Helmholtz contraction of the core.

Although the problem of modelling the formation of the Sun has been approached by many authors over a long period of time, in recent years the discussion in the general astronomical literature has come to focus on the work of Hayashi and his collaborators (see, e.g., Hayashi and Nakano 1965; Hayashi 1966; Narita, Nakano, and Hayashi 1970). So entrenched has become the Hayashi view that it is forgotten that even in the spherically symmetric case, with no rotation, no magnetic fields, or nuclear energy generation, the evolution of the pre-main sequence Sun depends critically on the starting conditions. In the approach of Hayashi one begins with a centrally condensed object *highly* unstable against gravitational collapse (very Jeans unstable), and obtains the following familiar picture of the subsequent evolution: after a free-fall contraction the core undergoes a pair of bounces and heats up rapidly, forming a rather large and luminous hydrostatic equilibrium. The core becomes completely convective and the protostar approaches the Zero-Age Main Sequence along an almost vertical path in the Hertzsprung-Russell luminosity color (or effective temperature) diagram, as discussed by Newkirk and Gough at this conference. However, one is troubled by how the protosun achieved the somewhat developed structure (centrally peaked polytropic density distribution) assumed by Hayashi as an initial condition. Thus Larson (1968, 1969a,b, 1972) was led to consider the conceptually simpler, but computationally considerably more difficult picture of the self-gravitational collapse of an initially uniform *slightly* gravitationally unstable tenuous interstellar cloud of large radius, an object far removed from the stellar state initially. Unfortunately, the dynamic evolution which follows from these simple starting conditions is so difficult computationally that Larson was unable to perform the hydrodynamic calculation without the introduction of additional physical assumptions concerning, for example, the structure of the accretion shock front. Hayashi ([illegible] and others questioned the validity of these assumptions, and the work of Larson was not universally accepted. In the years that followed many authors (e.g., Appenzeller and Tscharnuter 1975; Westbrook and Tarter 1975; Ruppel and Cloutman 1975; Bertout 1976; Winkler 1976, 1978; Tscharnuter and Winkler 1979; for additional references see the review papers of Woodward 1978, Larson 1973, 1978, and Bodenheimer and Black 1978) attempted the calculation starting from initial conditions similar to Larson's, in an attempt to settle the question of the validity of Larson's auxilliary physical assumptions. Recently Winkler and Newman (1980a) have given a critical analysis of the influence of numerical techniques in this type of calculation, and have performed a hydrodynamic calculation free of additional assumptions. They have given a detailed account of the structure in the region of the accretion shock, and find that Larson's assumptions are well satisfied for the case of the 1 $M_\odot$ protostar. Thus Larson's account of the evolution of the early Sun is a correct statement of the consequences of the initial condition of a uniform tenuous interstellar cloud, if rotation, magnetic fields, and thermonuclear reactions are neglected. Winkler and Newman (1980b) have discussed the effects on the evolution of a detailed description of the equation of state and opacity. The discussion which follows is intended to give a simple overview of the protostellar evolution. It is based on the latter two papers, and on an additional calculation in which the effects of convective energy transport were taken explicitly into account. As it turns out, the inclusion of the mixing length theory of convection into the treatment of the collapse and accretion process of the early Sun is only of minor importance, and leads essentially to the same stellar structure as that found in earlier calculations in which convection was neglected.

As in Hayashi's work spherical symmetry is assumed and the effects of magnetic fields, rotation, and nuclear energy generation are neglected. The initial and boundary conditions employed in the present calculation are given in Table 1. One solar mass was assumed to be distributed initially in a diffuse interstellar cloud of radius 1.5×10^{17} cm (0.16 light year), with uniform density 1.4×10^{-19} g cm^{-3} (equivalent to about 4.2×10^{4} H_2 molecules per cm^{3}, a moderately dense cloud), at a uniform temperature of 10 K, embedded in a constant external radiation field of temperature 10 K. The resulting configuration was slightly Jeans unstable to self-gravitational collapse, with an initial free-fall time $t_{ff} = 1.8 \times 10^{5}$ years. The total mass, the cloud radius, and the temperature of the external radiation field were held constant throughout the calculation, and the resulting hydrodynamic evolution was followed numerically by the method of Tscharnuter and Winkler (1979).

The resulting evolution of the protostellar cloud was found to proceed in the following way. After about one initial free-fall time t_{ff} the initial collapse phase ends and a hydrostatic core forms. A second collapse ensues when temperatures in the hydrostatic core are high enough for hydrogen dissociation to begin. Eventually this collapse is halted and the final hydrostatic core is formed. In the accretion process which follows the remaining envelope material rains onto the central core. During this process the kinetic energy of the free-falling material is transformed almost completely into outgoing radiation in the strong accretion shock surrounding the core. Therefore, in contrast to Hayashi's work, the bulk of the gravitational energy released is not deposited in the heating of the material of the hydrostatic stellar core. A fully convective core does not develop. Since the gravitational energy release is continually radiated away over a long period of time (some 10^{5} years), the hydrostatic core which results is rather small and of low luminosity ($L_{max} \approx 30 L_{\odot}$) compared to that of Hayashi. Throughout the accretion process the luminosity is generated almost entirely in the accretion shock, the core itself contributing only about 1 $L_{\odot}$ to the total luminosity. Less than about 0.5 $L_{\odot}$ was carried by convective energy transport in the hydrogen ionization zone beneath the surface of the hydrostatic core. At the end of the accretion phase a stellar core of about $2R_{\odot}$ radiates about 1 $L_{\odot}$.

In the following some details of the evolution are presented. Fig. 1 shows the evolution of the center of the protostar in the log ρ-log T diagram. The course of the evolution is determined by the thermodynamic properties of the hydrogen-helium-dust mixture used in the calculation, as emphasized by Winkler and Newman (1980b). (The particular composition employed had a hydrogen mass fraction $X = 0.7$, helium mass fraction $Y = 0.28$, with the remaining $0.02\ M_\odot$ in the form of heavier elements, distributed as in the King IVa mixture of Cox and Tabor 1976, and 1 % of the total material present in the form of dust grains.) The initial dynamic collapse (a-b in Fig. 1) is isothermal, the gravitational energy released being radiated away immediately. However, when the central density reaches about 10^{-13} g cm^{-3} the material begins to become optically thick to radiation. The central regions begin to heat up, and the pressure increases. The collapse is halted at point b in Fig. 1, and the first hydrostatic core is formed. The core contracts quasi-statically from b to c, while matter rains down upon it from the freely falling envelope. At central temperatures of a few thousand K hydrogen molecules begin to dissociate, and the gravitational energy release begins to go into internal modes of freedom of the gas. The pressure increase slows, and a second dynamic collapse (c-d in Fig. 1) results. The final stellar core forms as the dissociation nears completion, and a bounce occurs. A double shock front structure persists for a time, until the material between the shocks has fallen onto the inner shock front. The second collapse occurs so quickly (time scale ~ 10^4 sec.) that the gravitational energy released in the late stages of the collapse cannot be radiated away as rapidly as it is generated. A luminosity peak results, and propagates to the cloud boundary on a time scale of about a year, producing a luminosity outburst of about 10-15 $L_\odot$ (Fig. 3) at the surface. The stellar core contracts quasistatically from d to f, growing as the free-falling envelope is accreted in near stationary fashion. At point e in Fig. 1 an off-center temperature maximum develops due to the interplay of electron degeneracy and pressure ionization effects.

as discussed by Winkler and Newman (1980b). The calculation was terminated at point f when 99 % of the mass had been accumulated in the core; the position of the temperature maximum had reached the radial track of the present Sun in the log ρ-log T diagram, but the central regions had not yet reached the point g characteristic of the mature Sun. This material will be heated (in part by nuclear energy generation) in the subsequent Kelvin-Helmholtz contraction of the early Sun to its position on the Zero-Age Main Sequence.

In Fig. 2 an account of the evolution of the convective region during the accretion process is given. Here the position (in mass coordinates) of the convection zone is shown as a function of the core mass. A hydrogen ionization zone exists in the upper layers of the hydrostatic core just downstream of the accretion shock, which marks the boundary between the stellar equilibrium and the free falling envelope. In this zone the adiabatic gradient ∇_{ad} drops to about 0.1 or even less, and a convectively unstable region is established. However this region contains at most a few % of the total mass; a flux of only order 0.5 $L_{\odot}$ is carried in this region. Deeper in the core below the ionization zone the adiabatic gradient rapidly approaches values of order 0.3 to 0.4, characteristic of an almost completely ionized material, and this material remains stable against convection early in the accretion process. The variation of the size of the convection zone at times when 20 to 60 % of the material is assembled in the core reflects changes in ∇_{ad} as well as in the actual temperature gradient d lnT/d lnP as the evolution proceeds. The core grows in both mass and radius until about 50-60 % of the material is in the core; a significant contraction of the core material resulting in an increase of the internal energy of the gas is not found prior to this evolutionary stage. After 60 % of the total material has fallen onto the core, the core finally begins to contract, the core radius decreasing by about 50 % in the remainder of the accretion process. This contraction heats the core material somewhat, so that the actual temperature gradient approaches the adiabatic gradient in approximately the outer half of the stellar core at the end of the accretion phase. The contribution of this well-established convection zone to the total luminosity is also approximately 0.5 $L_{\odot}$, and therefore it is unimportant for most of the accretion phase, as a comparison with the total luminosity shown in Fig. 1 reveals.

The evolution in the luminosity-effective temperature (Hertzsprung-Russell) diagram is shown in Fig. 3. In contrast to the tracks of Hayashi, the evolution begins physically, with low luminosity and low effective temperature. The numbers labelling the curve are the time in years since the formation of the final stellar core some 2.43×10^5 years after the initial collapse begins. It requires about 1 year for the luminosity outburst produced at the end of the second collapse to reach the outer cloud boundary, and this energy is quickly dissipated. The luminosity then increases slowly for about 10^4 years and remains roughly constant for about 2.5×10^5 years as the envelope is accreted onto the core. At about 2.35×10^5 years following the formation of the final core the point where the optical depth equals 2/3 (the effective "photosphere") passes rapidly through the optically thin pre-heating region outside the shock front and enters the shock front region itself as the envelope becomes depleted of material. A sharp increase in effective temperature and a jump to the left in the diagram result. The difficulties associated with the interpretation of effective temperature in star formation calculations have been discussed by Winkler and Newman (1980a). The luminosity decreases as the envelope depletion proceeds and the mass flow rate drops toward zero.

The present calculation was terminated when 99 % of the matter had been accreted by the core, and did not include thermonuclear reactions. Presumably the protostar would approach the Sun's position on the Zero-Age Main Sequence in the usual fashion with the ignition of the proton-proton chains, after having followed a path in the Hertzsprung-Russell diagram very different from that found by Hayashi and his colleagues. However, the exhaustion of light primordial fuels (e.g., deuterium, ^{3}He, ^{7}Li, etc.), which was not considered in either the present calculation nor those of Hayashi, could profoundly affect the evolution. The point at which a particular fuel becomes an important energy source depends on the electron shielding correction, which is a difficult problem for the relatively high density, low temperature conditions encountered in star formation (Newman 1978). However, deuterium ignition may be expected to occur at a stage when only about 10 % of the mass has been accreted by the core, an off-center temperature maximum occurs, and 0.03 $M_\odot$ (nearly 1/3 of the core) resides in a degenerate region (Winkler and Newman 1980b). Thermonuclear ignition under these circumstances may be quite interesting. The onset of nuclear burning should be off-center, outside a degenerate region with nearly temperature-independent pressure response. A weak flash or thermonuclear runaway might result, with possible consequences for the structure of the flow. Fresh fuel will be continually delivered from above as the accretion proceeds, and it is not clear that the evolution resulting will resemble closely that discussed above, which neglects nuclear energy sources. The role of thermonuclear reactions in a dynamic pre-main sequence setting is the subject of current investigation (Newman and Winkler 1980).

REFERENCES

Appenzeller, I. and Tscharnuter, W. 1975, Astr. Astrophys., 40, 397.

Bertout, C. 1976, Astr. Astrophys., 51, 101.

Bodenheimer, P. 1978, Astrophys. J., 224, 488.

Bodenheimer, P. and Black, D. C. 1978, in *Protostars and Planets*, ed. T. Gehrels (Tucson: Univ. of Arizona Press), p. 288.

Cox, A. N. and Tabor, J. E. 1976, Astrophys. J. Suppl., 31, 271.

Disney, M. J. 1976, Mon. Not. Roy. Astr. Soc., 175, 323.

Gough, D. O. 1980, these Proceedings.

Hayashi, C. 1966, Ann. Rev. Astr. Astrophys., 4, 171.

Hayashi, C. 1970, Proceedings of the 15th Liege International Astrophysical Symposium, p. 127.

Hayashi, C. and Nakano, T. 1965, Progr. Theor. Phys., 34, 754.

Kondo, M. 1978, The Moon and the Planets, 19, 245.

Larson, R. B. 1968, Ph. D. thesis, Caltech (University Microfilms order number 68-13, 070).

Larson, R. B. 1969a, Mon. Not. Roy. Astr. Soc., 145, 271.

Larson, R. B. 1969b, Mon. Not. Roy. Astr. Soc., 145, 297.

Larson, R. B. 1972, Mon. Not. Roy. Astr. Soc., 157, 121.

Larson, R. B. 1973, Fund. Cosmic Phys., 1, 1.

Larson, R. B. 1978, in *Protostars and Planets*, ed. T. Gehrels (Tucson: Univ. of Arizona Press), p. 43.

Narita, S., Nakano, J., and Hayashi, C. 1970, Progr. Theor. Phys., 43, 942.

Newkirk, G., Jr. 1980, these Proceedings.

Newman, M. J. 1978, in Proceedings of the 22nd Liege International Astrophysical Symposium "Les Elements et leurs Isotopes dans l'Univers".

Newman, M. J. and Winkler, K.-H. A. 1980 (in preparation for Astrophys. J.).

Ruppel, H. M. and Cloutman, L. D. 1975, Los Alamos Scientific Laboratory Report LA-6140-MS.

Tscharnuter, W. and Winkler, K.-H. A. 1979, Computer Phys. Comm., 18, 171.

Westbrook, C. K. and Tarter, C. B. 1975, Astrophys. J., 200, 48.

Winkler, K.-H. A. 1976, Ph. D. thesis, University of Göttingen (issued as Technical Report MPI/PAE-Astro 90 by the Max-Planck-Institut für Physik und Astrophysik, Munich; English translation in UCRL-Trans-11206).

Winkler, K.-H. A. 1978, The Moon and the Planets, 19, 237.

Winkler, K.-H. A. and Newman, M. J. 1980a, Astrophys. J., 236, 000 (in press, February, 1980).

Winkler, K.-H. A. and Newman, M. J. 1980b, Astrophys. J., 238, 000 (in press, May, 1980).

Woodward, P. 1978, Ann. Rev. Astr. Astrophys., 16, 555.

Table 1. Initial and Boundary Conditions

$M = 1\ M_\odot$ = constant

$R = 1.5 \times 10^{17}$ cm = constant

$\rho = 1.4 \times 10^{-19}$ g cm^{-3} uniform initially

$T = 10$ K isothermal initially

$T_B = 10$ K = constant at boundary

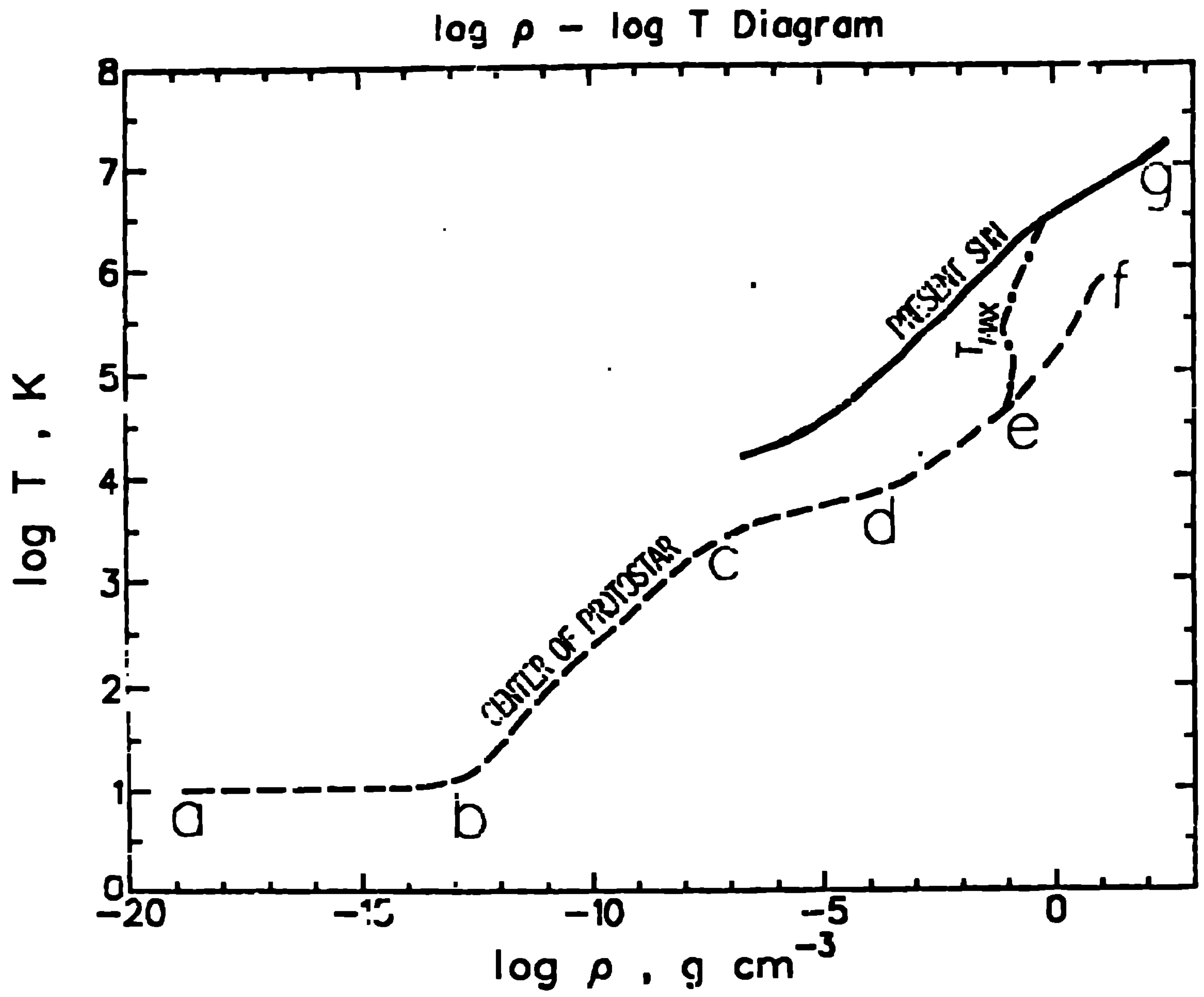
$t_{ff} = 1.8 \times 10^{5}$ years initially

FIGURE CAPTIONS

Fig. 1. Density-temperature diagram. The evolution of the central temperature and density of the pre-main sequence Sun is shown, as is the radial track of the present Sun. The path of the off-center temperature maximum which develops at point e is also given.

Fig. 2. The location of convectively unstable zones is shown as a function of core mass. The diagonal coincides with the outer boundary of an ionization zone at the edge of the protostellar core just downstream of the accretion shock.

Fig. 3. Evolutionary track in the Hertzsprung-Russell luminosity-effective temperature diagram. The numbers on the curve give the time in years since the formation of the final stellar core, 2.43 x 10^5 years after the initial collapse. The Zero-Age Main Sequence is also shown.


log ρ – log T Diagram
log T , K
log ρ , g cm^{-3}
0
1
2
3
4
5
6
7
8
−20
−15
−10
−5
0
a
b
c
d
e
f
g
CENTER OF PROTOSTAR
PRESENT SUN
T MAX

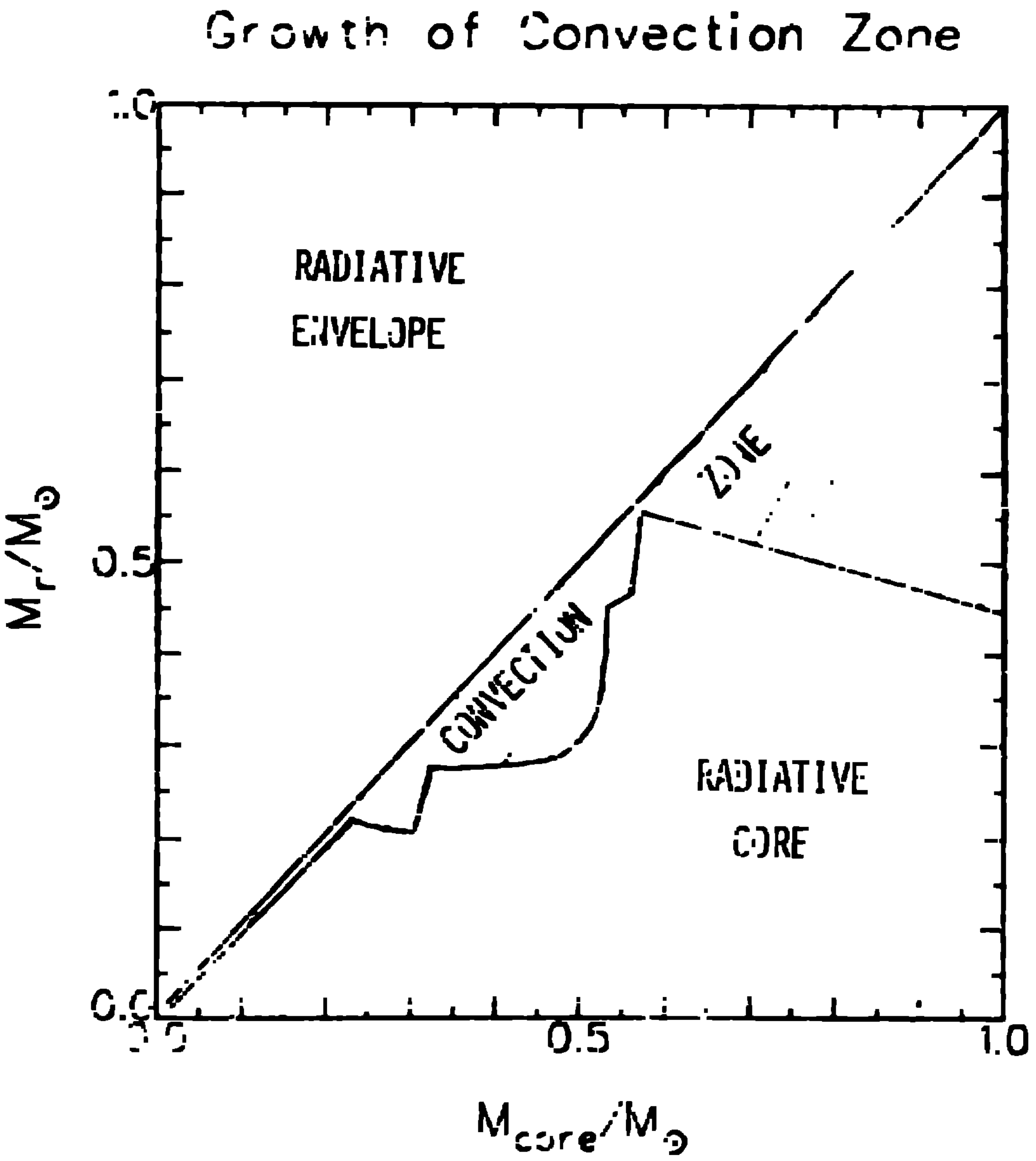

Growth of Convection Zone
1.0
0.5
0.0
0.0
0.5
1.0
$M_r/M_\odot$
$M_{core}/M_\odot$
RADIATIVE
ENVELOPE
CONVECTION
ZONE
RADIATIVE
CORE

Fig. 2

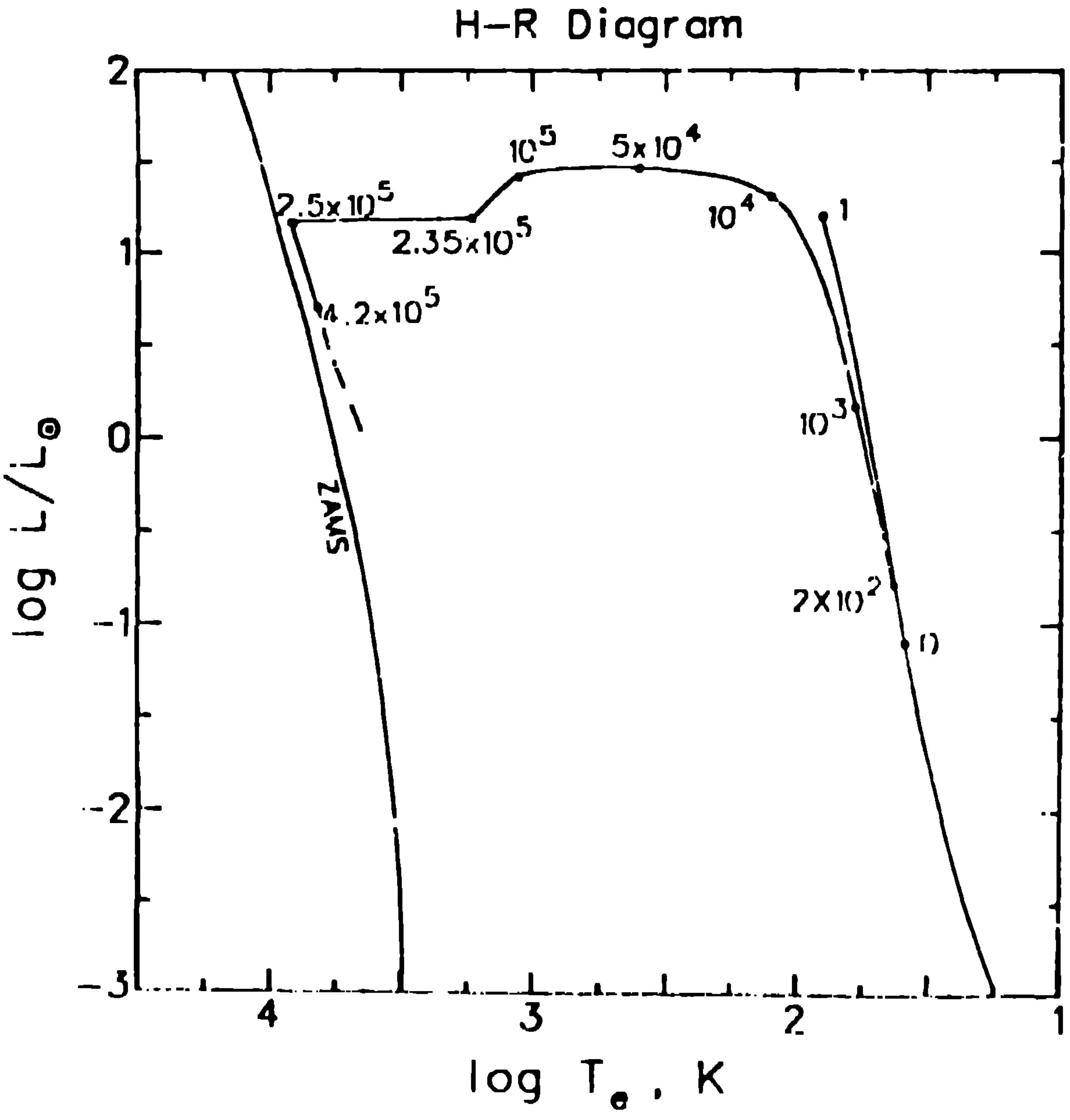

H–R Diagram
log L/L⊙
log Tₑ , K
2
1
0
-1
-2
-3
4
3
2
1
ZAMS
2.5×10⁵
2.35×10⁵
10⁵
5×10⁴
10⁴
1
4.2×10⁵
10³
2×10²
0

Fig. 3