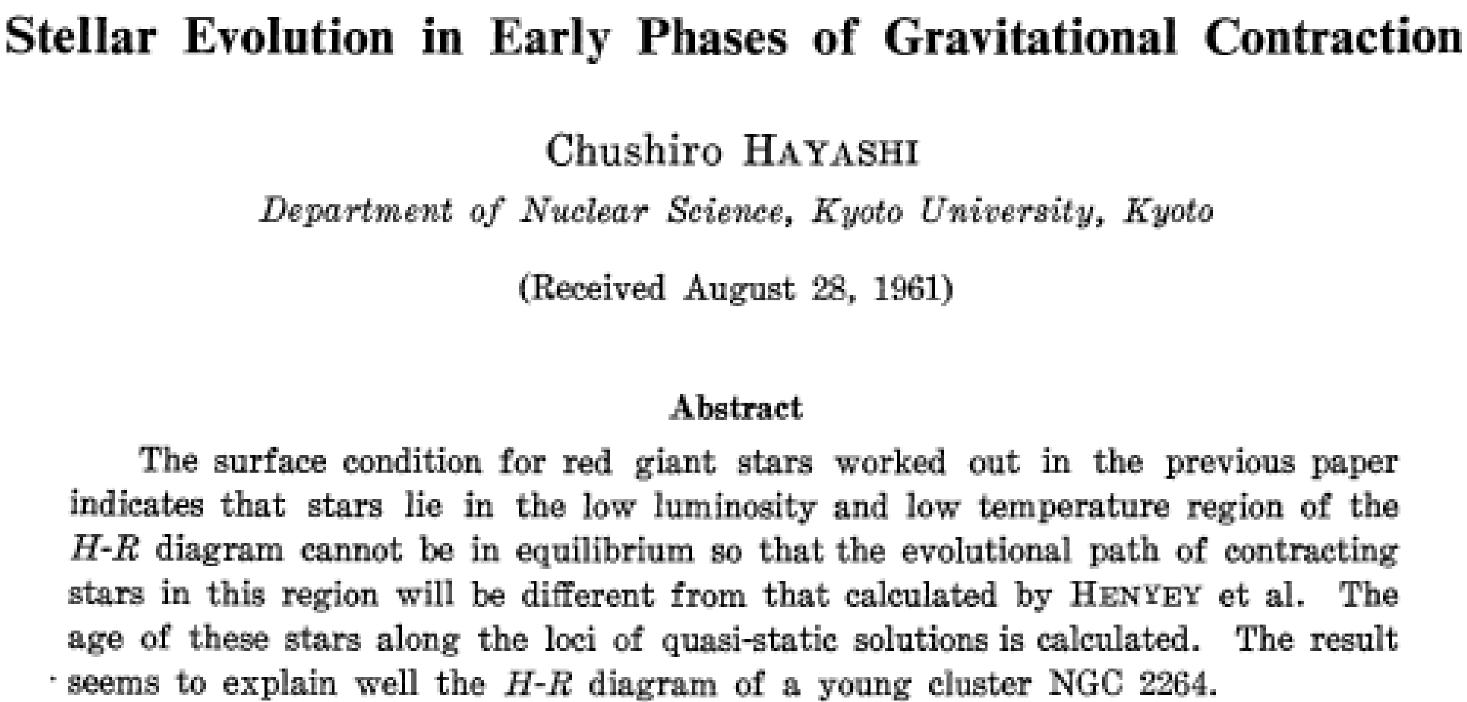
Prof. Hayashi's Work on the Pre-Main-Sequence Evolution and Brown Dwarfs

Takenori NAKANO
(Kyoto)

First Star IV May 21, 2012, Kyoto

Prof. Hayashi in early 1961

Hayashi 1961 Publ. Astr. Soc. Japan **13**, 450



Stellar Evolution in Early Phases of Gravitational Contraction

Chushiro HAYASHI
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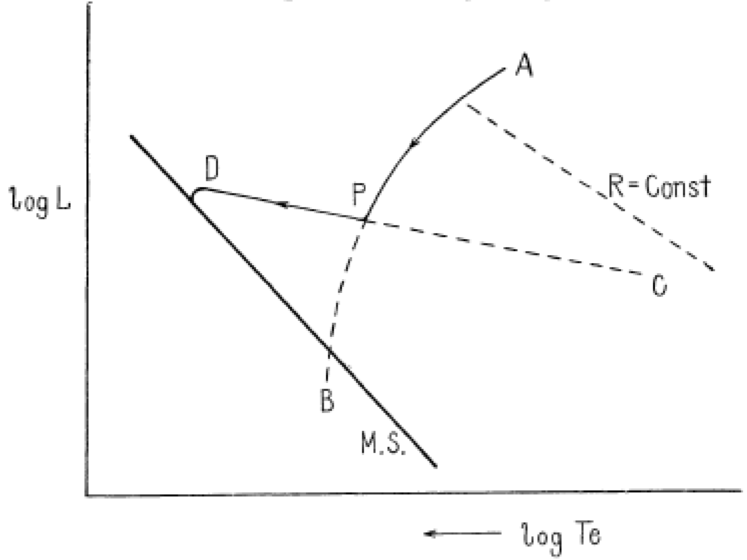
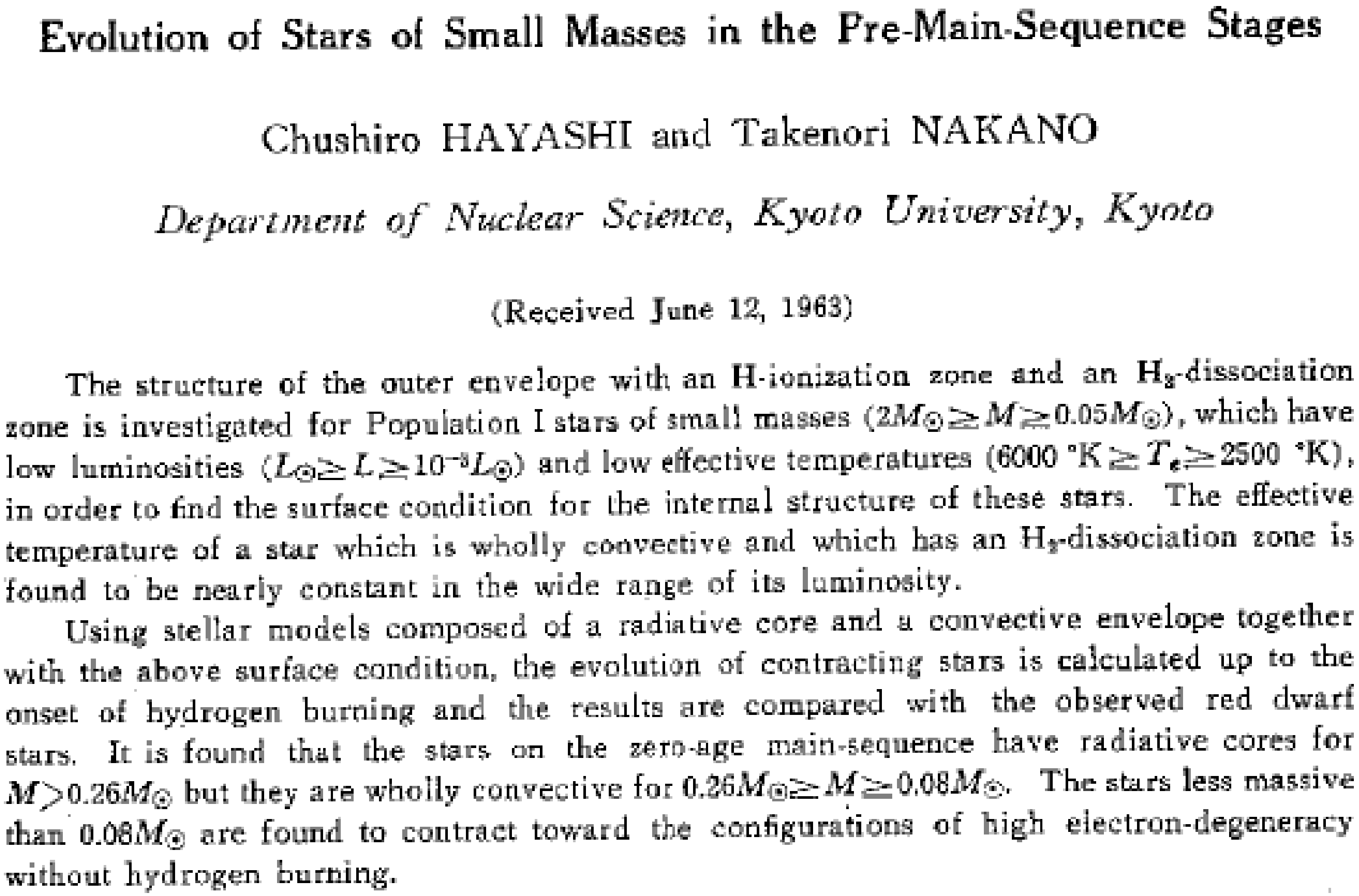
(Received August 28, 1961)

Abstract

The surface condition for red giant stars worked out in the previous paper indicates that stars lie in the low luminosity and low temperature region of the *H-R* diagram cannot be in equilibrium so that the evolutional path of contracting stars in this region will be different from that calculated by HENYEY et al. The age of these stars along the loci of quasi-static solutions is calculated. The result seems to explain well the *H-R* diagram of a young cluster NGC 2264.



Hayashi & Nakano 1963 Prog. Theor. Phys. **30**, 460



Evolution of Stars of Small Masses in the Pre-Main-Sequence Stages

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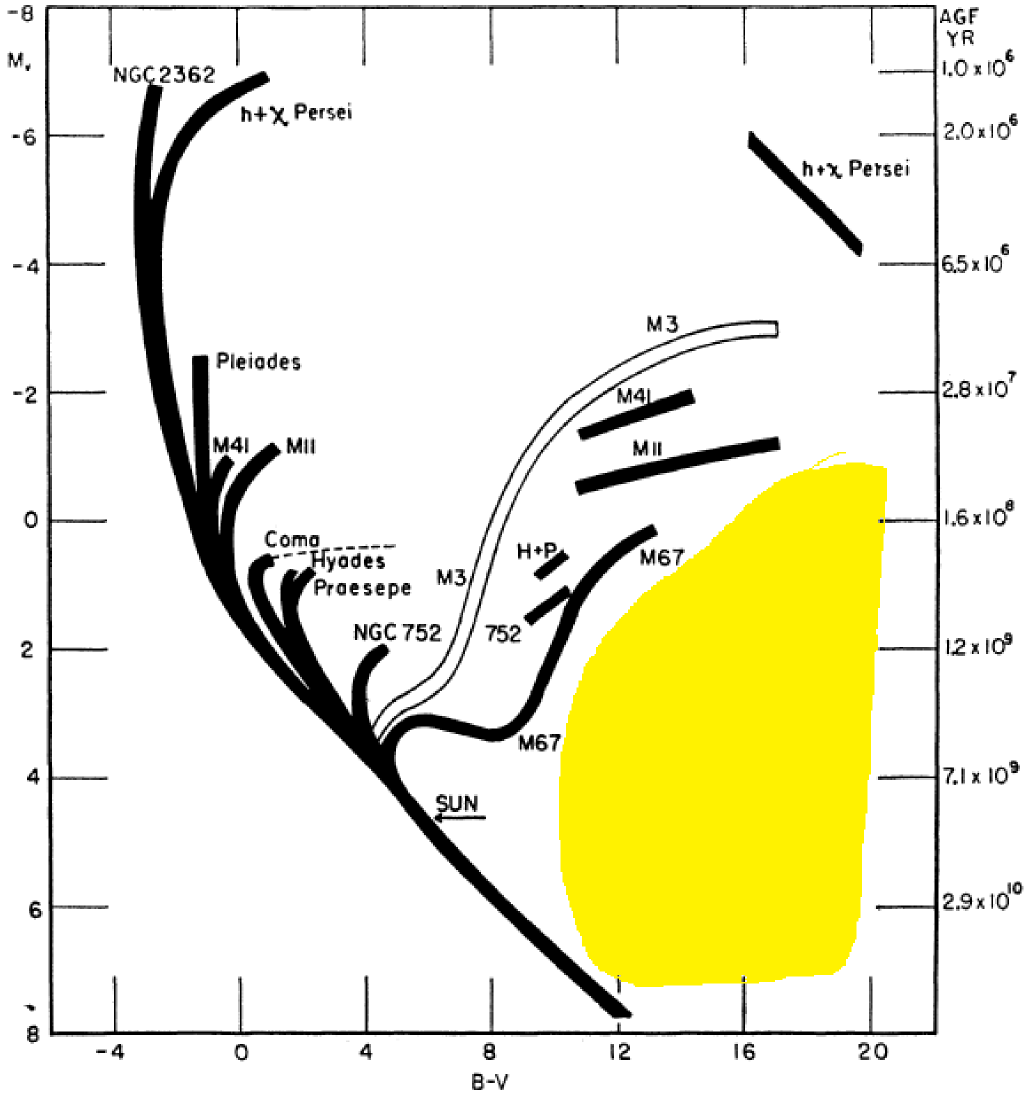
(Received June 12, 1963)

The structure of the outer envelope with an H-ionization zone and an H_2-dissociation zone is investigated for Population I stars of small masses ($2M_\odot \geq M \geq 0.05M_\odot$), which have low luminosities ($L_\odot \geq L \geq 10^{-3}L_\odot$) and low effective temperatures ($6000\ °K \geq T_e \geq 2500\ °K$), in order to find the surface condition for the internal structure of these stars. The effective temperature of a star which is wholly convective and which has an H_2-dissociation zone is found to be nearly constant in the wide range of its luminosity.

Using stellar models composed of a radiative core and a convective envelope together with the above surface condition, the evolution of contracting stars is calculated up to the onset of hydrogen burning and the results are compared with the observed red dwarf stars. It is found that the stars on the zero-age main-sequence have radiative cores for $M > 0.26M_\odot$ but they are wholly convective for $0.26M_\odot \geq M \geq 0.08M_\odot$. The stars less massive than $0.08M_\odot$ are found to contract toward the configurations of high electron-degeneracy without hydrogen burning.

Discovery of the Hayashi Phase



Sandage 1957

HR diagram of star clusters

no stars at

T_{eff} < several x 10^3 K

(yellowed)

Reason for this unknown in 1950s

e.g., Sandage & Schw. 1952

Regarded as peculiar to advanced stage not applicable to pre-main sequence stage

e.g., Henyey et al. 1955

Brownlee & Cox 1961

Boundary Conditions at Stellar Surface

H-ionization zone

inside the photosphere in cool stars

makes the atmosphere convectively unstable

suppresses the decrease of T_{eff}

Previous work

neglected the convection induced by H-ioniz. zone

Hayashi & Hoshi 1961

structure of the atmosphere with H-ioniz. zone

⇒ boundary condition for the internal structure

Energy Transport in the star

by radiation and convection

Convection occurs where $ds/dr < 0$

effectively, specific entropy s = const

Temperature gradient

$$\nabla_{\rm rad} \equiv \left(\frac{d\log T}{d\log P}\right)_{\rm rad} = \frac{\kappa L_r}{16\pi c G M_r}\frac{3P}{aT^4}$$: radiative zone

$$\nabla_s \equiv \left(\frac{d\log T}{d\log P}\right)_s$$: convection zone

Convection occurs only when $\nabla_{\rm rad} > \nabla_s$

usually $\nabla_{\rm rad} \sim 1$

fully ioniz. gas with negl. rad. press. $\nabla_s = 0.4$

H-ionization zone $\nabla_s \sim 0.1$

Convection easily occurs

decrease of log T << decrease of log P, log ρ

polytrope

Hayashi & Hoshi 1961

determined by numerical calculation

the critical effective temperature $T_{\rm eff}^{\rm (cr)}(M_\bigstar, R_\bigstar)$

$T_{\rm eff} = T_{\rm eff}^{\rm (cr)}$: Emden solution for a polytrope of $N = 1.5$

$\Rightarrow$ fully convective star

$T_{\rm eff} > T_{\rm eff}^{\rm (cr)}$: centrally condensed type sol. for $N = 1.5$

$\rho = \infty$, $M_r > 0$ at $r = 0$

can be fitted at $r > 0$ with a regular sol. with $N > 1.5$

star with convective envelope and radiative core

$T_{\rm eff} < T_{\rm eff}^{\rm (cr)}$: collapsed type sol.(N=1.5) $M_r = 0$ at $r > 0$

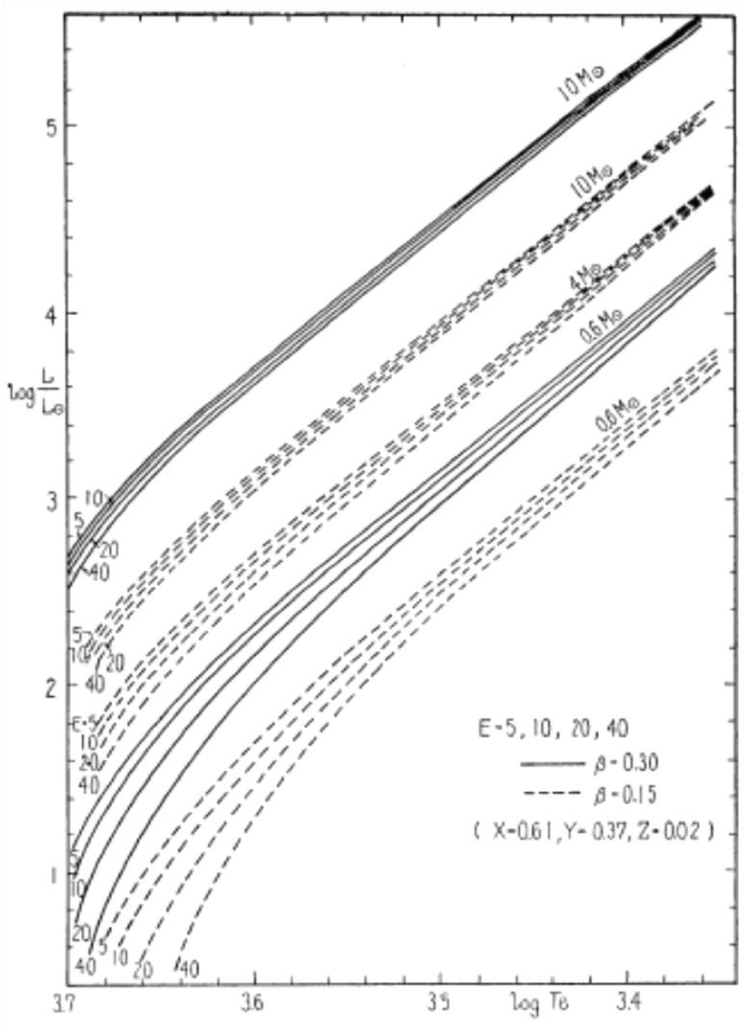
can be fitted at $M_r > 0$

only with a regular core sol. with $N < 1.5$

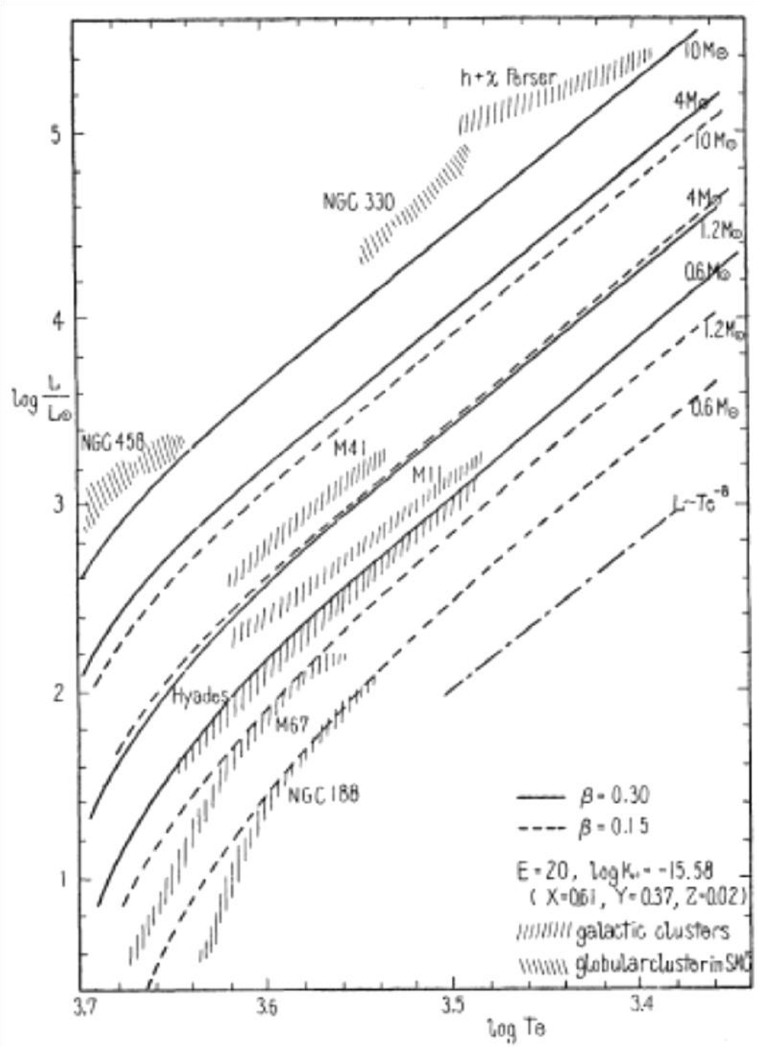
Such cores are convectively unstable, $N \rightarrow 1.5$

Stars cannot be in hydrostatic equil. with such $T_{\rm eff}$

Hayashi & Hoshi 1961 Publ. Astr. Soc. Japan **13**, 442



For each stellar mass the lowest curve is close to $T_{\mathrm{eff}}^{(\mathrm{cr})}$

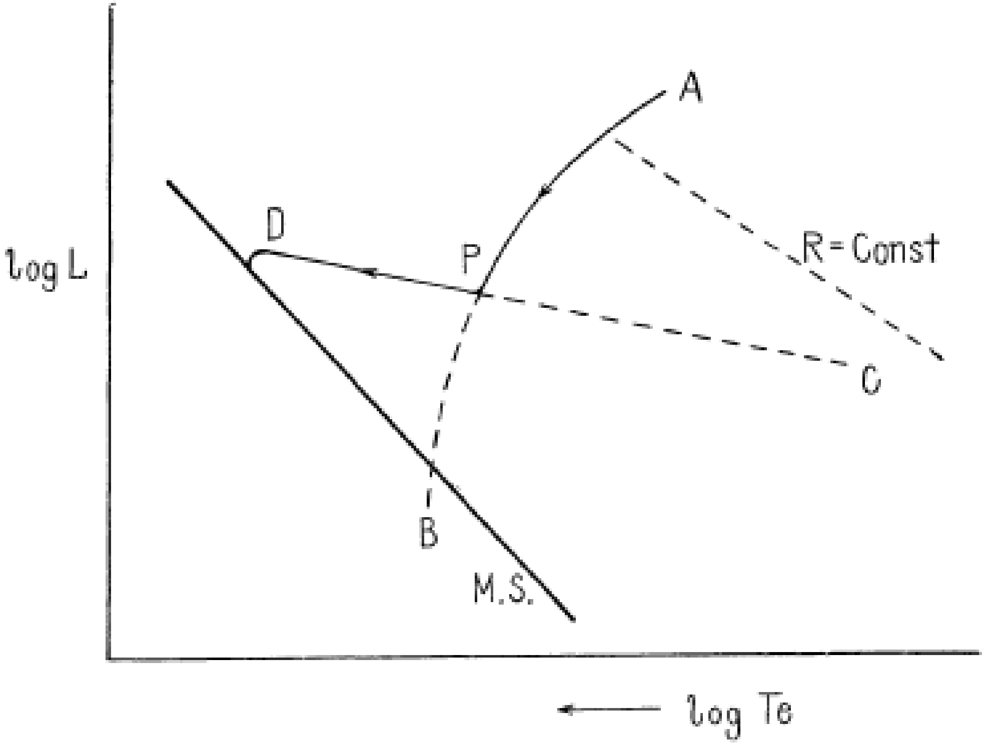


Comparison with open clusters

Hayashi 1961 Publ. Astr. Soc. Japan **13**, 450

$T_{\mathrm{eff}}^{\ (\mathrm{cr})}$ should be applied to any stage of stellar evolution

pre-main sequence stage is not an exception



APB : $T_{\mathrm{eff}} = T_{\mathrm{eff}}^{\ (\mathrm{cr})}$

Hayashi line

CPD : Henyey track

AP : Hayashi track

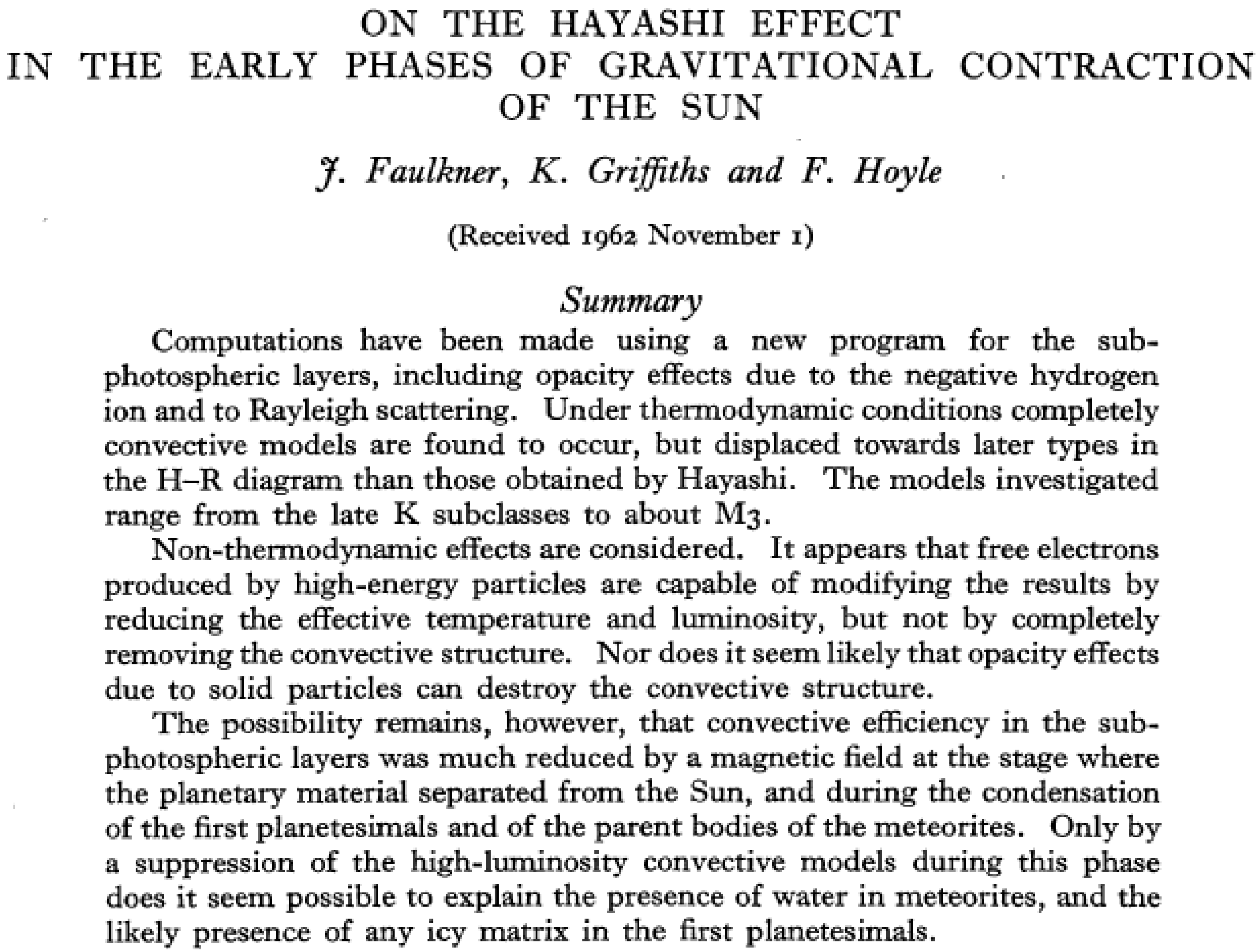
Hayashi phase

right side of APB :

Hayashi's forbidden region

on Hayashi track: more luminous, contract faster

Faulkner, Griffiths & Hoyle 1963 MNRAS **126**, 1



ON THE HAYASHI EFFECT IN THE EARLY PHASES OF GRAVITATIONAL CONTRACTION OF THE SUN

J. Faulkner, K. Griffiths and F. Hoyle

(Received 1962 November 1)

Summary

Computations have been made using a new program for the sub-photospheric layers, including opacity effects due to the negative hydrogen ion and to Rayleigh scattering. Under thermodynamic conditions completely convective models are found to occur, but displaced towards later types in the H–R diagram than those obtained by Hayashi. The models investigated range from the late K subclasses to about M3.

Non-thermodynamic effects are considered. It appears that free electrons produced by high-energy particles are capable of modifying the results by reducing the effective temperature and luminosity, but not by completely removing the convective structure. Nor does it seem likely that opacity effects due to solid particles can destroy the convective structure.

The possibility remains, however, that convective efficiency in the sub-photospheric layers was much reduced by a magnetic field at the stage where the planetary material separated from the Sun, and during the condensation of the first planetesimals and of the parent bodies of the meteorites. Only by a suppression of the high-luminosity convective models during this phase does it seem possible to explain the presence of water in meteorites, and the likely presence of any icy matrix in the first planetesimals.

Mechanisms which can reduce $T_{\mathrm{eff}}^{(\mathrm{cr})}$ greatly ?

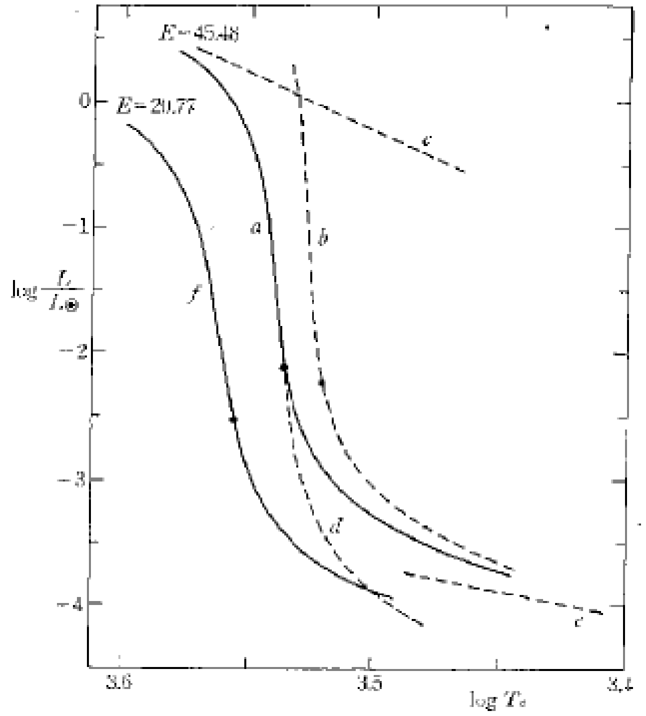
Pre-main sequence evolution of low-mass stars

Hayashi & Nakano 1963

As $M_\star$ decreases, $T_{\mathrm{eff}}^{(\mathrm{cr})}$ decreases.

H_2 molecules form in the atmosphere

H_2-dissociation zone inside the photosphere



$M_\star = 0.2\ M_\odot$

makes the atmosphere

convectively unstable

suppresses the decrease of T_{eff}

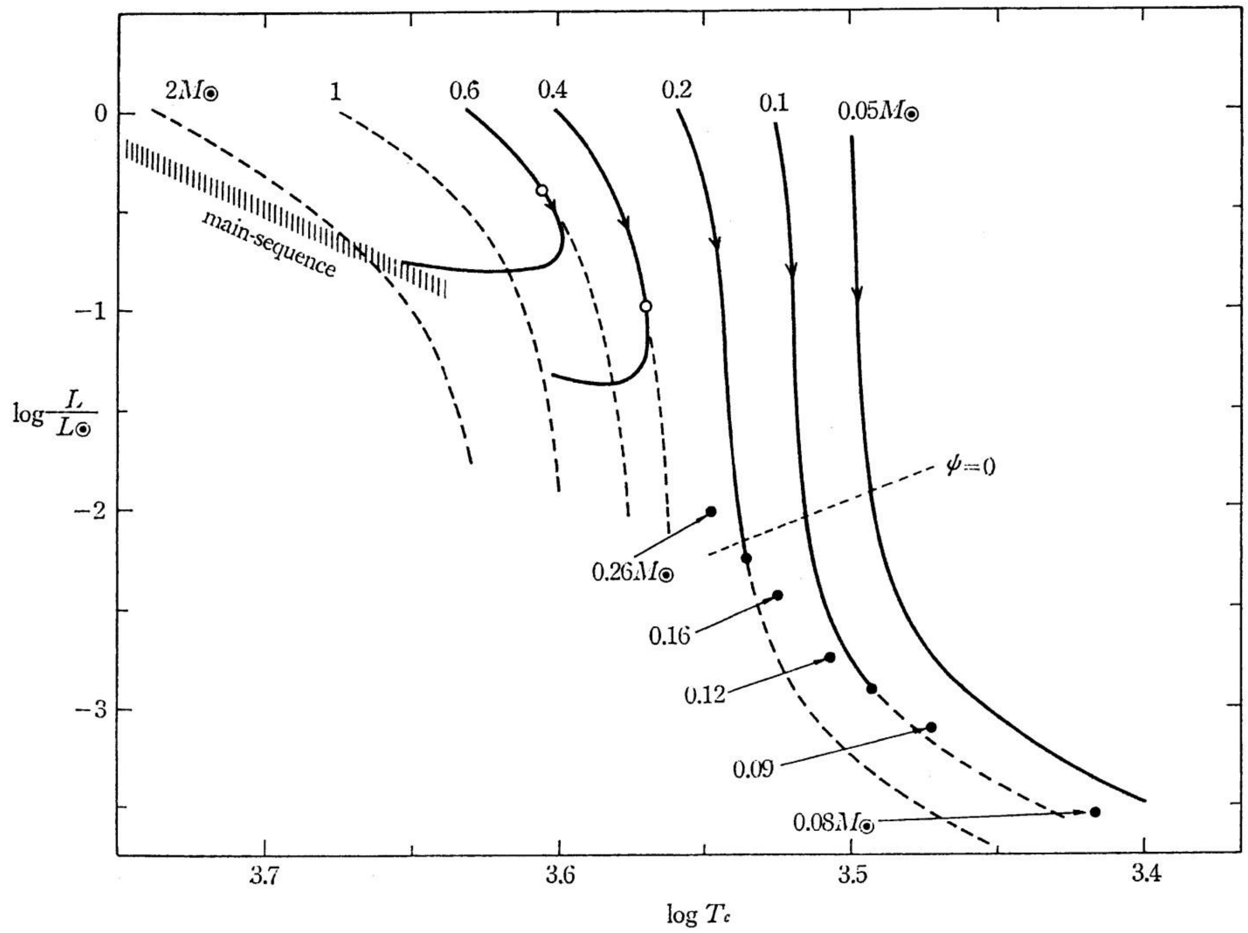
same as H-ioniz. zone

H_2-dissociation has great effect

a : Hayashi line

c : Hayashi line without H_2

Evolutionary paths on the HR diagram



For smaller $M_\star$,
longer Hayashi phase
shorter Henyey phase

$M_\star \leq 0.26\ M_\odot$,
no Henyey phase
dot : ZAMS

brown dwarfs

ZAMS (zero-age main sequence)

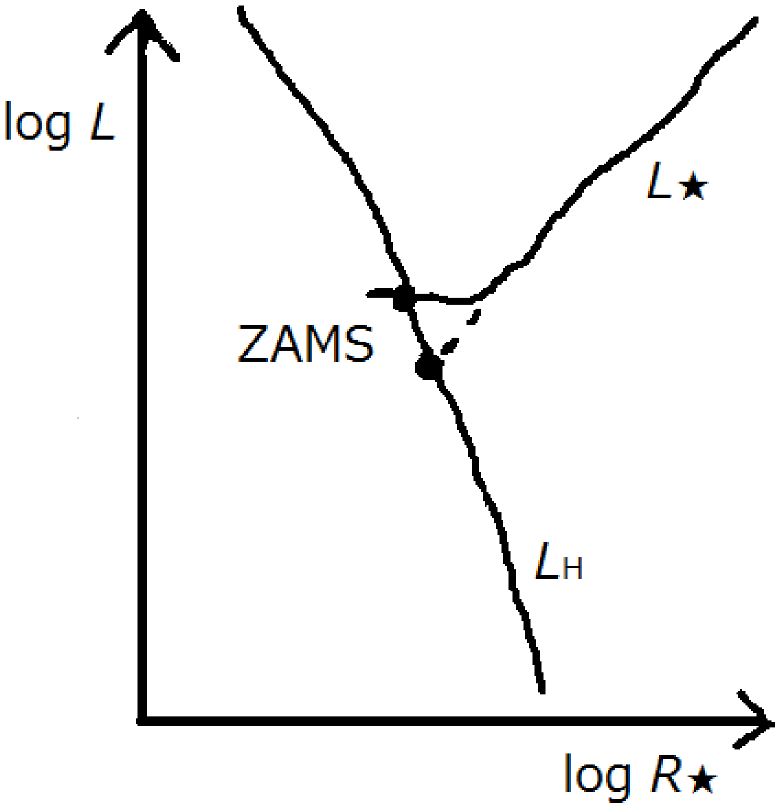
the stage at which $L_\bigstar = L_\mathrm{H}$ holds for the first time
in the pre-main sequence contraction phase

L_H : energy released by H-burning per unit time
determined by the structure of the central region

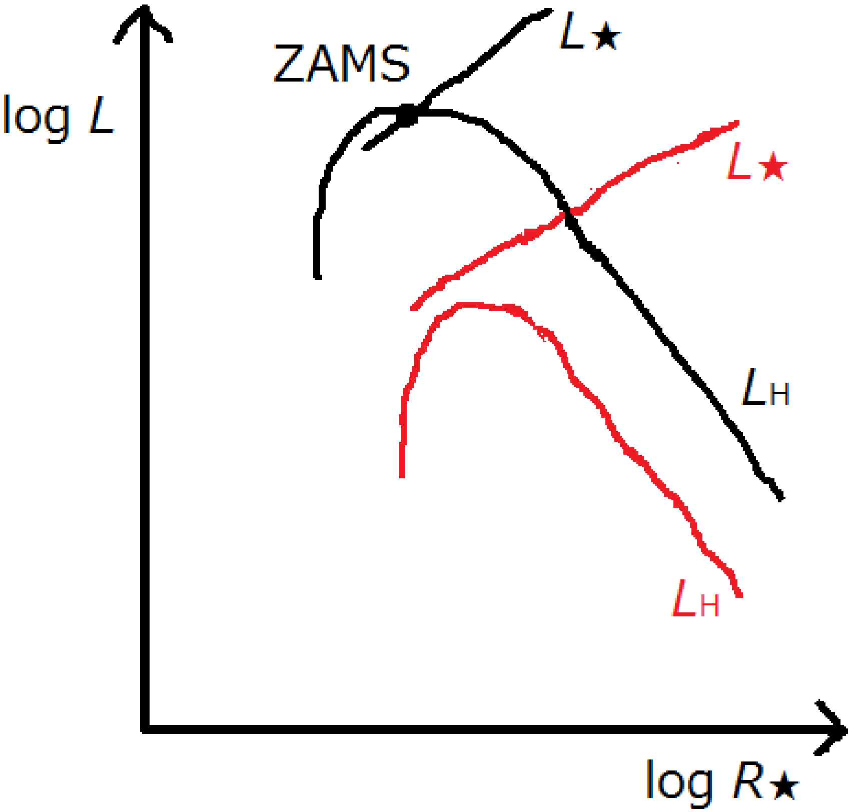
$L_\bigstar$: energy emitted from the stellar surface per unit time
in general, determined by the whole structure of ★
for a fully convective star,
determined by the Hayashi line and $R_\bigstar$

To determine ZAMS for a given $M_\bigstar$,
we need both L_H and $L_\bigstar$ as functions of $R_\bigstar$

Determination of ZAMS and bottom of main sequence



Stars of not very small mass



Stars of very small mass
Electrons degenerate
as the star contracts.

SSK

Evolution of a 0.07 $M_\odot$ star

⇓

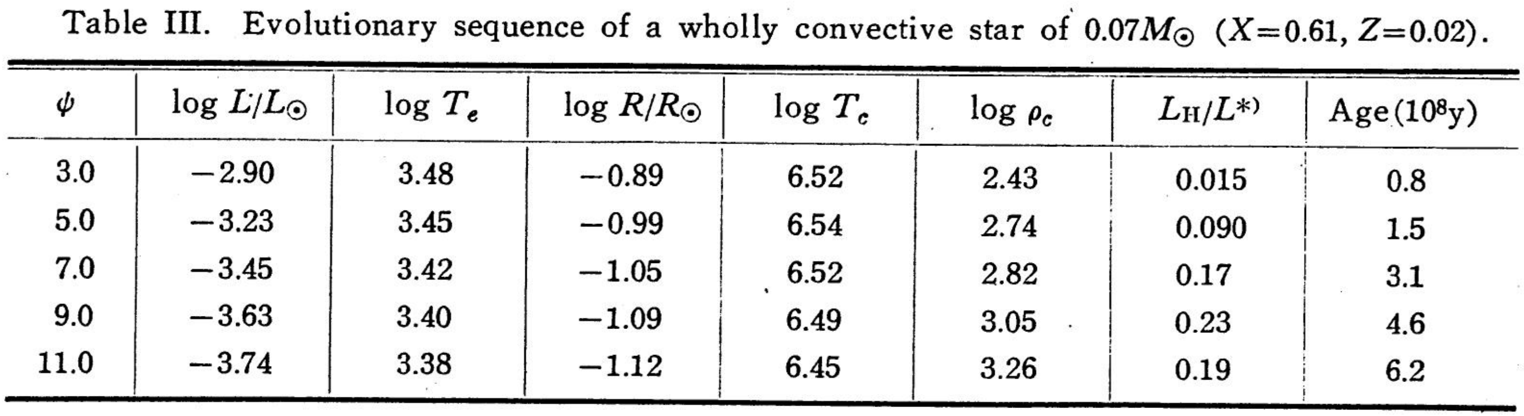


Table III. Evolutionary sequence of a wholly convective star of $0.07M_\odot$ ($X=0.61$, $Z=0.02$).

ψ	$\log L/L_\odot$	$\log T_e$	$\log R/R_\odot$	$\log T_c$	$\log \rho_c$	$L_{\mathrm{H}}/L^{*)}$	Age (10^8y)
3.0	−2.90	3.48	−0.89	6.52	2.43	0.015	0.8
5.0	−3.23	3.45	−0.99	6.54	2.74	0.090	1.5
7.0	−3.45	3.42	−1.05	6.52	2.82	0.17	3.1
9.0	−3.63	3.40	−1.09	6.49	3.05	0.23	4.6
11.0	−3.74	3.38	−1.12	6.45	3.26	0.19	6.2

⇐

Maximum value of $L_{\mathrm{H}} / L_\bigstar = 0.23$ at $\log R_\bigstar / R_\odot = -1.09$

cannot settle down on the main sequence

Lower mass limit to the main sequence

ours : between 0.08 and 0.07 $M_\odot$

the newest result (Burrows et al. 1997) :

between 0.08 and 0.075 $M_\odot$

Evolution of brown dwarfs

as an example, $M_\bigstar = 0.05\ M_\odot$ (Fig. 2 of HN 1963)

Kumar 1963a

Siv S. Kumar 1963, two short papers in Ap.J.

1. "Determined" the lower mass limits to main sequence
   0.07 $M_\odot$ for Pop. I, 0.09 $M_\odot$ for Pop. II
   "assuming reasonable luminosities for these stars (see the following paper)"
   detZAMS

2. Simple discussion on the evolution of brown dwarfs
   time required to contract to some $R_\bigstar$
   assuming $T_{\rm eff}$ = constant

degeneracy ?

High reputation for Kumar's papers

e.g., Ann. Rev. Astr. Astrophys. Vol.38 (2000)
two review articles on brown dwarfs

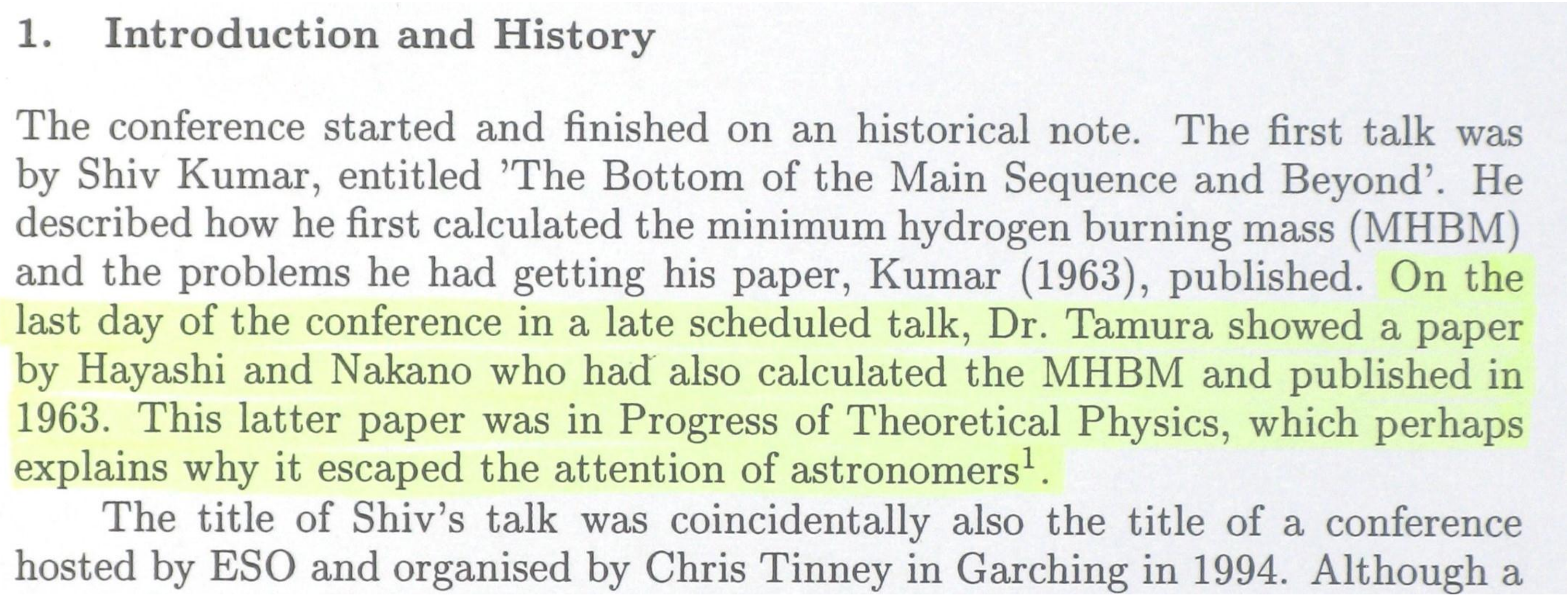
IAU Symposium No. 211 “Brown Dwarfs”
2002 Hawaii

Invited talk on history of research on brown dwarfs

Chairman of SOC allowed a Japanese participant
to give a short talk to introduce HN1963
just before the Summary Talk

A chance was given to me to write a short note
on HN1963 in the Proceedings (2003)

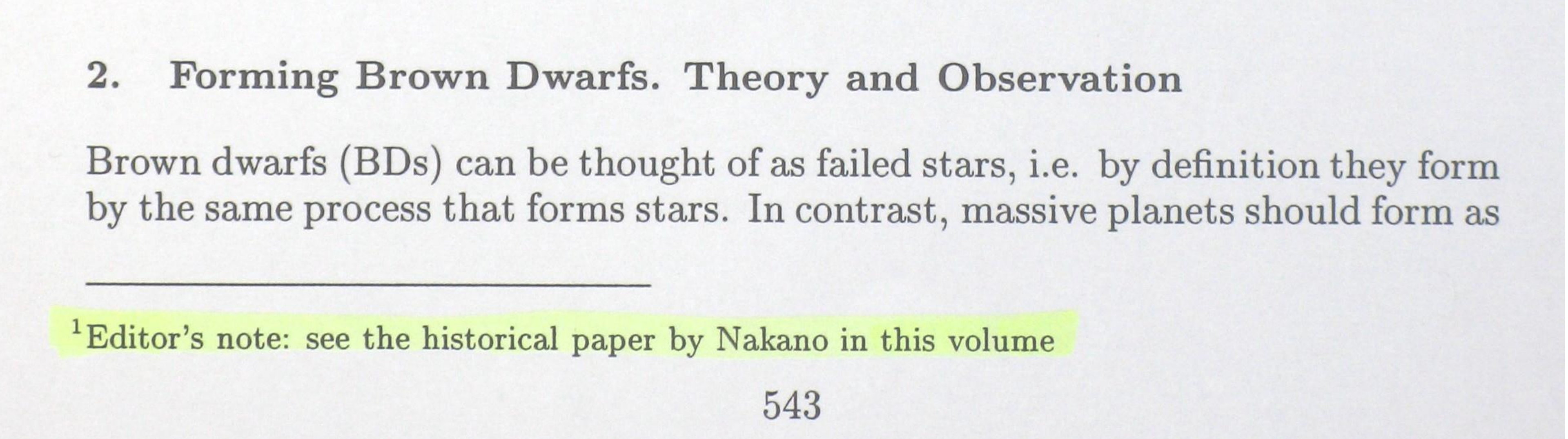
Conference Summary by R. F. Jameson



1. Introduction and History

The conference started and finished on an historical note. The first talk was by Shiv Kumar, entitled 'The Bottom of the Main Sequence and Beyond'. He described how he first calculated the minimum hydrogen burning mass (MHBM) and the problems he had getting his paper, Kumar (1963), published. On the last day of the conference in a late scheduled talk, Dr. Tamura showed a paper by Hayashi and Nakano who had also calculated the MHBM and published in 1963. This latter paper was in Progress of Theoretical Physics, which perhaps explains why it escaped the attention of astronomers[1].

The title of Shiv's talk was coincidentally also the title of a conference hosted by ESO and organised by Chris Tinney in Garching in 1994. Although a



2. Forming Brown Dwarfs. Theory and Observation

Brown dwarfs (BDs) can be thought of as failed stars, i.e. by definition they form by the same process that forms stars. In contrast, massive planets should form as

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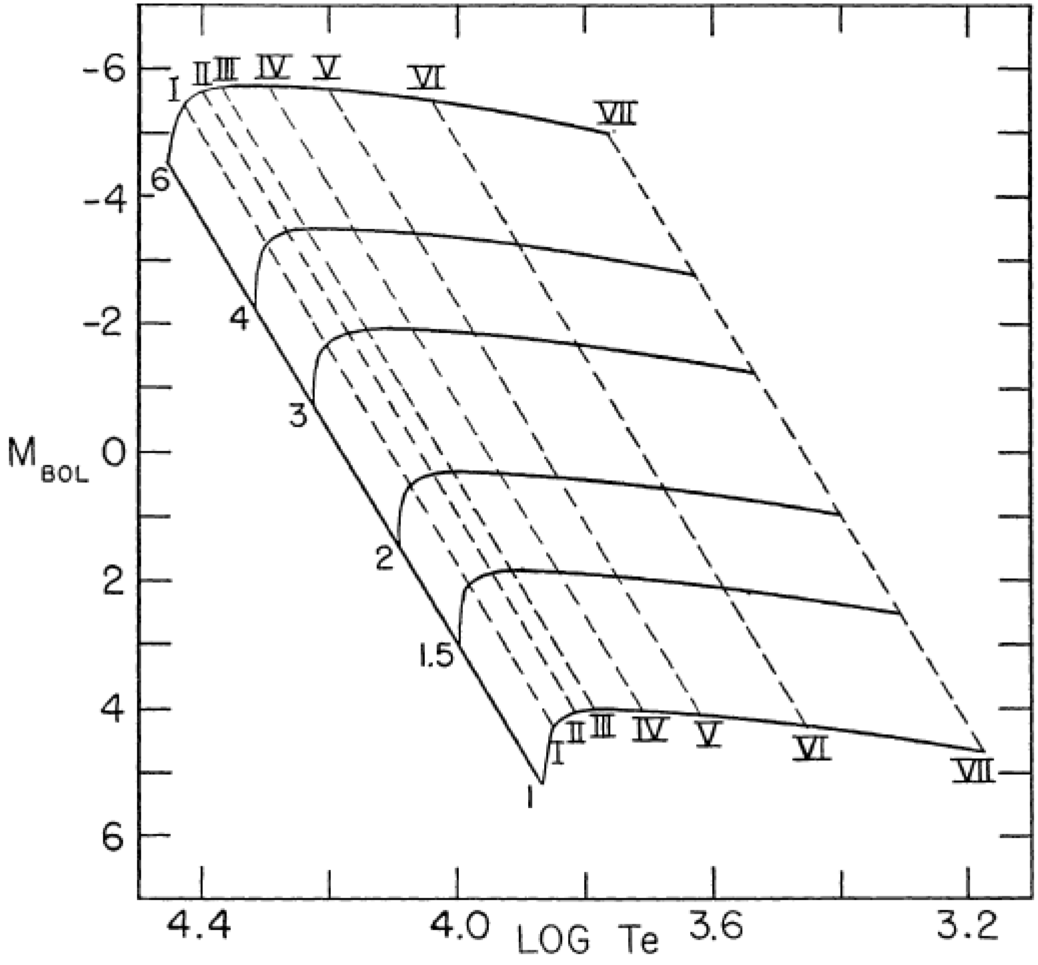
[1] Editor's note: see the historical paper by Nakano in this volume

Prof. Hayashi in 2008

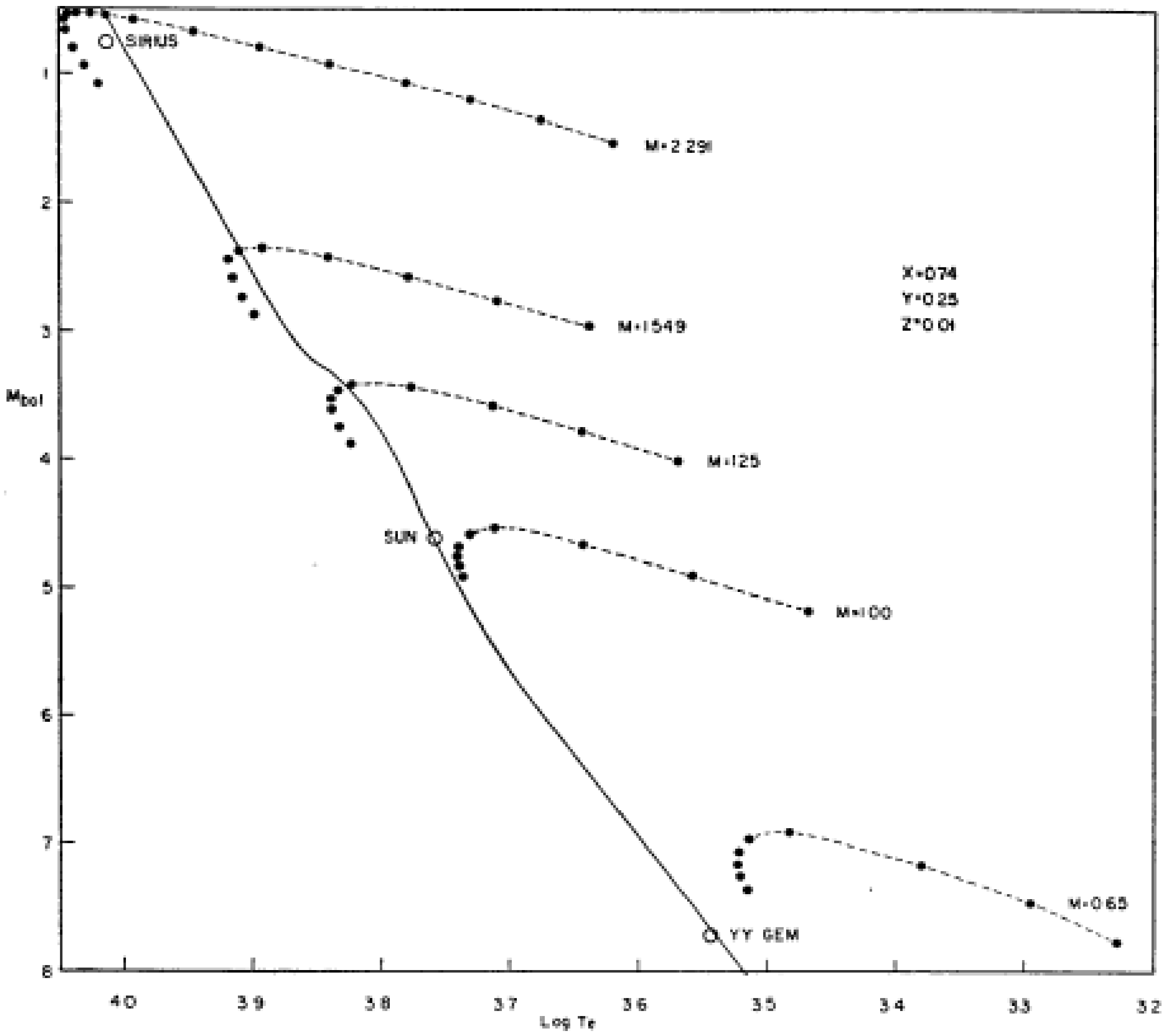
Sandage & Schwarzschild 1952



[Discov HP](#)

After hydrogen is exhausted in the core, T_{eff} continues to decrease.

Henyey, LeLevier, & Levee 1955



Pre-main-sequence evolution on the HR diagram

Discov HP

Brow Cox

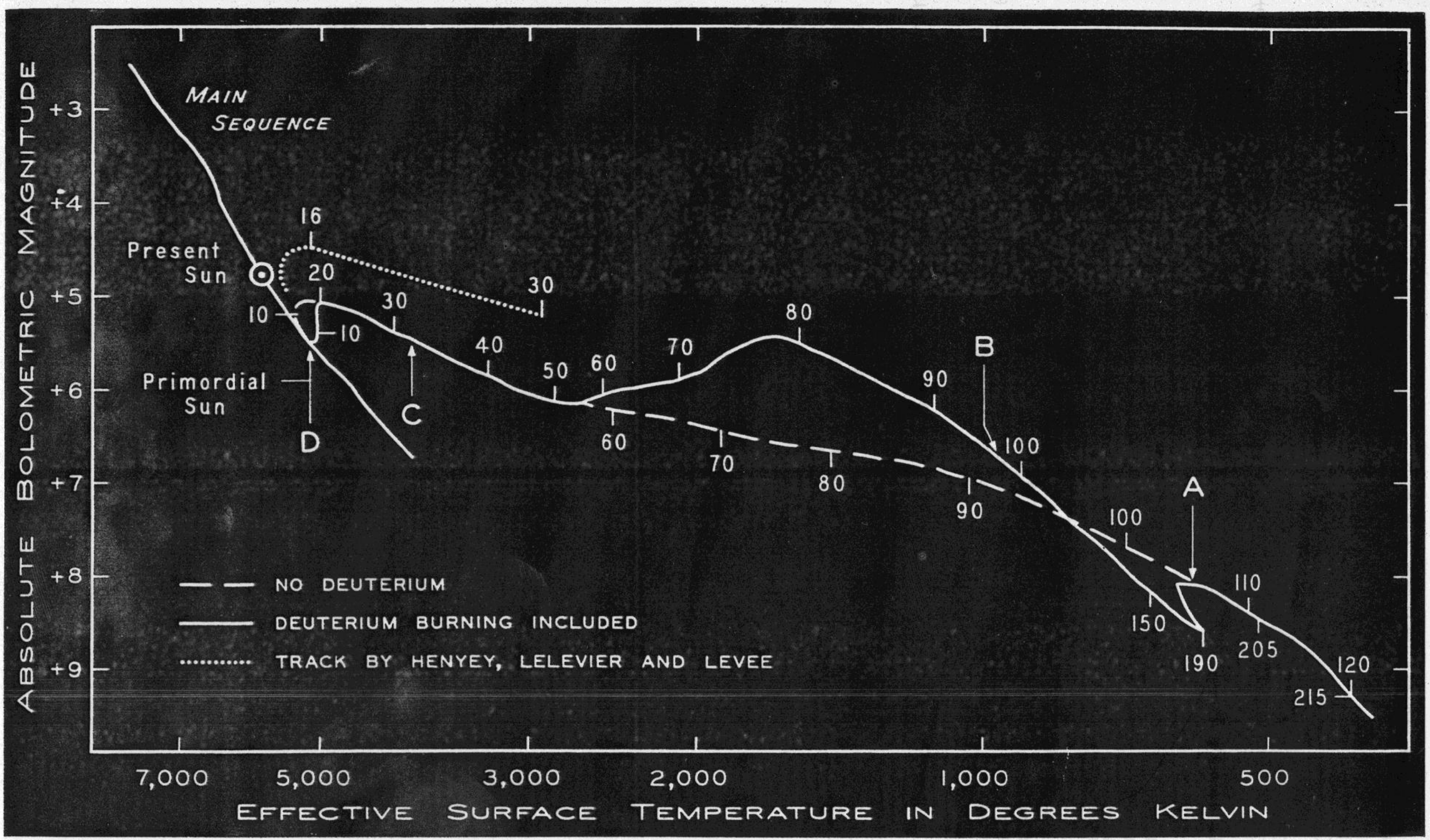


Fig. 5. Evolutionary tracks of three different model suns plotted on a theoretical Hertzsprung-Russell diagram. The tracks are labeled in millions of years before the main sequence is reached, matching Fig. 4. The letters A, B, C, and D correspond to those at the top of Fig. 4 and to the table of physical properties on page 256.

Brownlee & Cox 1961

Discov HP

Polytropic stars

HH 1961

$$\frac{dP}{dr} = -\frac{GM_r}{r^2}\rho$$
$$\frac{dM_r}{dr} = 4\pi r^2 \rho$$

Equation of state (polytropic) $P \propto \rho^{1+1/N}$

Change variables

$$\rho \propto \theta^N, \;\; P \propto \theta^{N+1} \;\;, \quad r \propto \xi$$
$$\frac{1}{\xi^2}\frac{d}{d\xi}\left(\xi^2 \frac{d\theta}{d\xi}\right) = -\theta^N$$
: Lane-Emden eq.

$$\Delta \log \rho = \frac{N}{N+1} \Delta \log P$$

For a given increase of pressure, Δ log *P*,
density increase Δ log ρ is larger for larger *N*

Fully convective stars ($N = 1.5$)

Center

$$\rho_{\mathrm{c}} = 5.99 \frac{3M_\star}{4\pi R_\star^3}$$

$$T_{\mathrm{c}} = 0.538 \frac{\mu m_{\mathrm{H}}}{k} \frac{GM_\star}{R_\star}$$

$s_{\mathrm{c}} = s_{\mathrm{c}}(\rho_{\mathrm{c}}, T_{\mathrm{c}})$: fn of $M_\bigstar$ and $R_\bigstar$

Photosphere

$M_\bigstar$, $R_\bigstar$, $T_{\mathrm{eff}} \rightarrow \rho_{\mathrm{ph}}$

$s_{\mathrm{ph}}(T_{\mathrm{eff}}, \rho_{\mathrm{ph}})$: fn of $M_\bigstar$, $R_\bigstar$ and T_{eff}

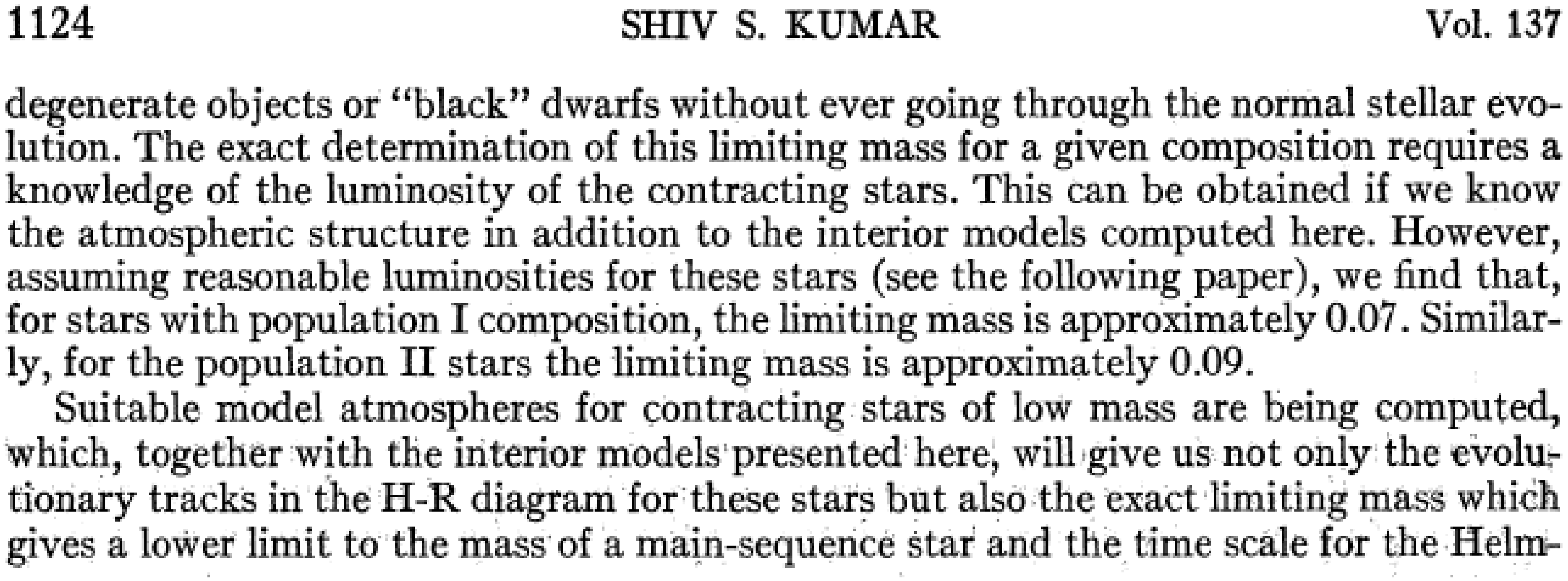
increasing fn of T_{eff} for given $M_\bigstar$ and $R_\bigstar$

For larger s (higher T_{eff}), lower ρ for given P

$\Rightarrow$ slower inward decrease of M_r

$\Rightarrow$ finite M_r remains at $r = 0$ (centrally condensed type)

Kumar 1963a, Ap.J. 137, 1121



degenerate objects or "black" dwarfs without ever going through the normal stellar evolution. The exact determination of this limiting mass for a given composition requires a knowledge of the luminosity of the contracting stars. This can be obtained if we know the atmospheric structure in addition to the interior models computed here. However, assuming reasonable luminosities for these stars (see the following paper), we find that, for stars with population I composition, the limiting mass is approximately 0.07. Similarly, for the population II stars the limiting mass is approximately 0.09.

Suitable model atmospheres for contracting stars of low mass are being computed, which, together with the interior models presented here, will give us not only the evolutionary tracks in the H-R diagram for these stars but also the exact limiting mass which gives a lower limit to the mass of a main-sequence star and the time scale for the Helm-

Kumar

Annular Sun

cover page