# 恒星進化モデルの進展

斉尾英行(東北大学・天文)

# 恒星進化モデルを変革した「発見」

- Nuclear energy source; Bethe (1939), Weizäcker(1938)
- Mixing-length model; Vitense(1953)
- Hayashi-boundary; Hayashi(1961)
- Henyey method; Henyey et al (1964)
- Helium-shell flash (Thermal pulse) の発見
  Schwartshild & Härm(1965)
- Mass exchange and merger in close binary systems;
  Webbink(1984), Iben & Tutukov (1984)
- OPAL & OP opacity tables; Rogers & Iglesias(1992)
  Seaton et al. (1994)

# Mixing-length theory を太陽モデルに

Zeitschrift für Astrophysik, Bd. 32, S. 135—164 (1953).

## Die Wasserstoffkonvektionszone der Sonne.

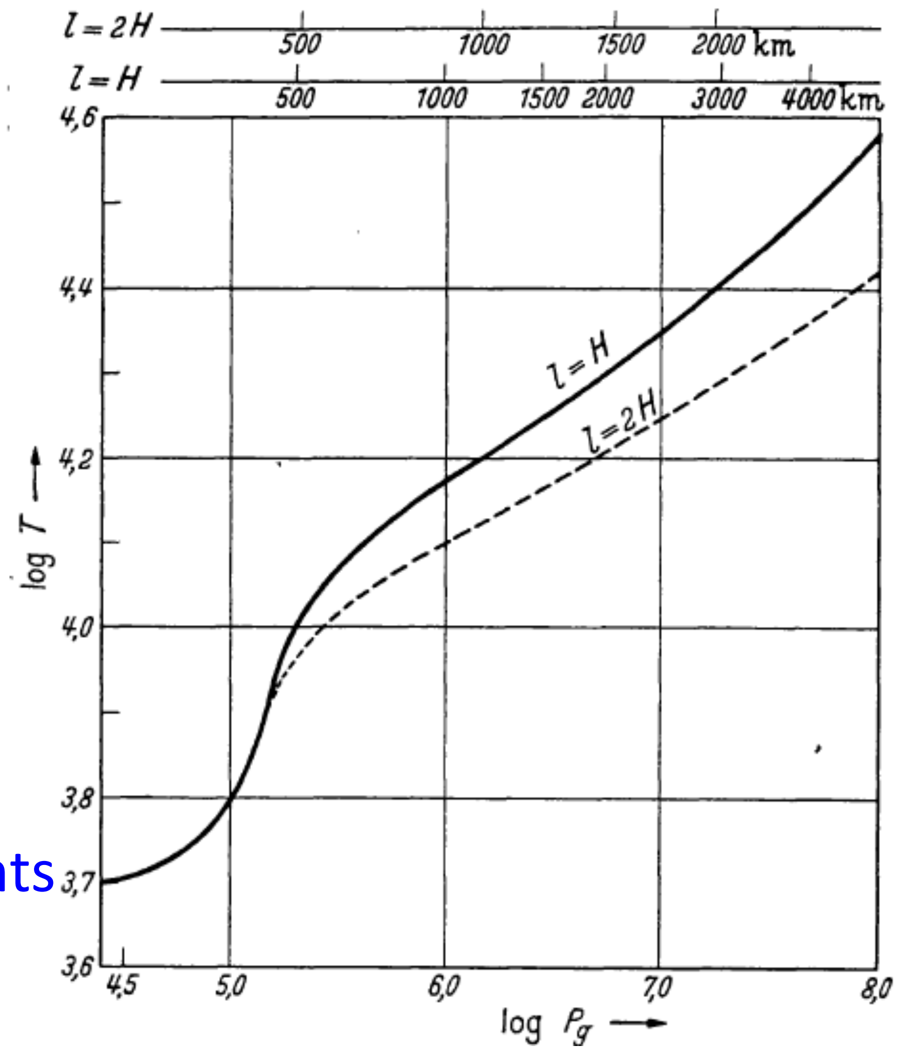
Von

ERIKA VITENSE,

$$\pi F_k = c_p \cdot \varrho \cdot T \cdot \bar{v} \cdot \frac{l}{2H} [\nabla - \nabla']$$

$$\bar{v}^2 = g \cdot \frac{l^2}{4H} \cdot [\nabla - \nabla'] \qquad \left(\nabla \equiv \frac{d \ln T}{d \ln P}\right)$$

$$\pi F_k + \pi F_{Str} = \pi F = \sigma T_e^4 ;$$




Super-adiabatic temperature gradients can be calculated

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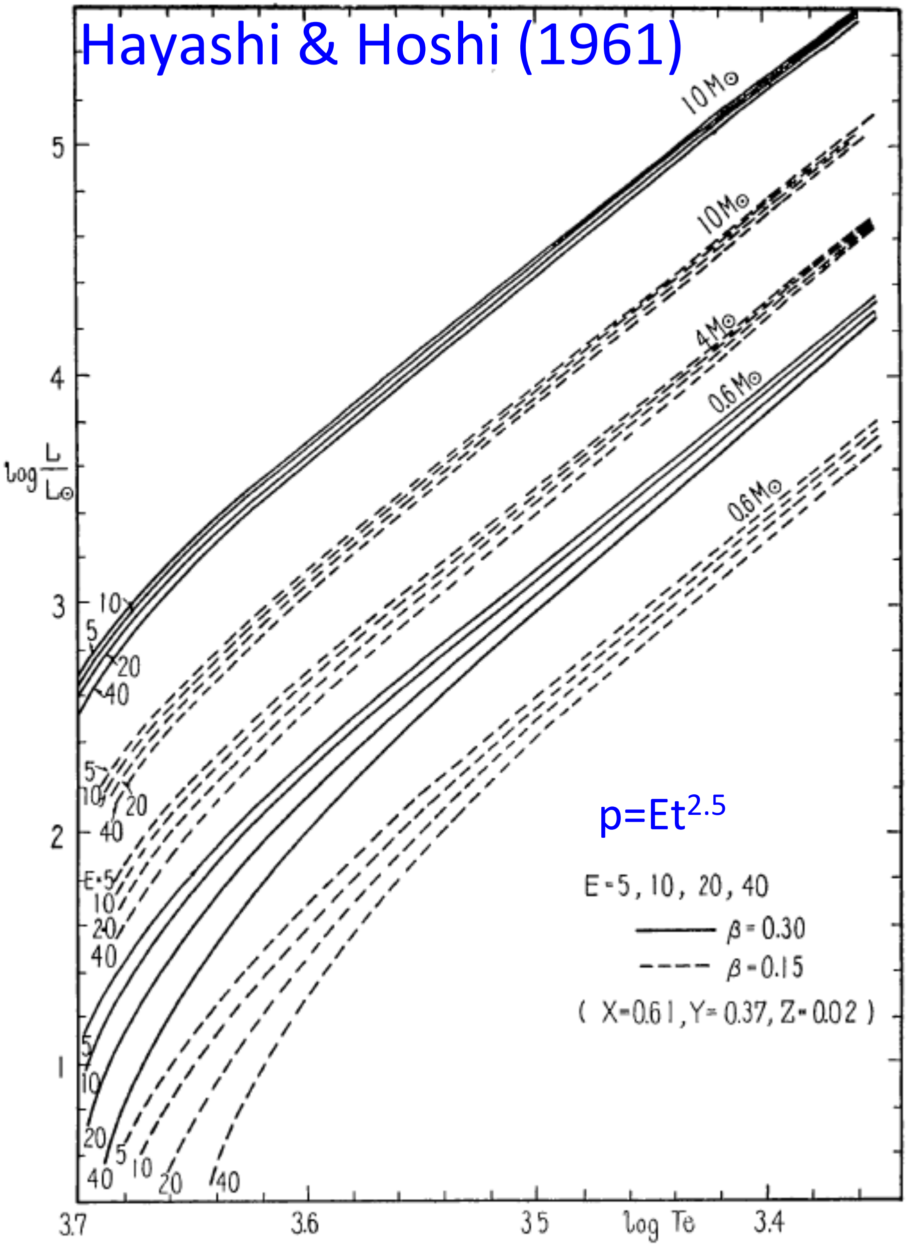
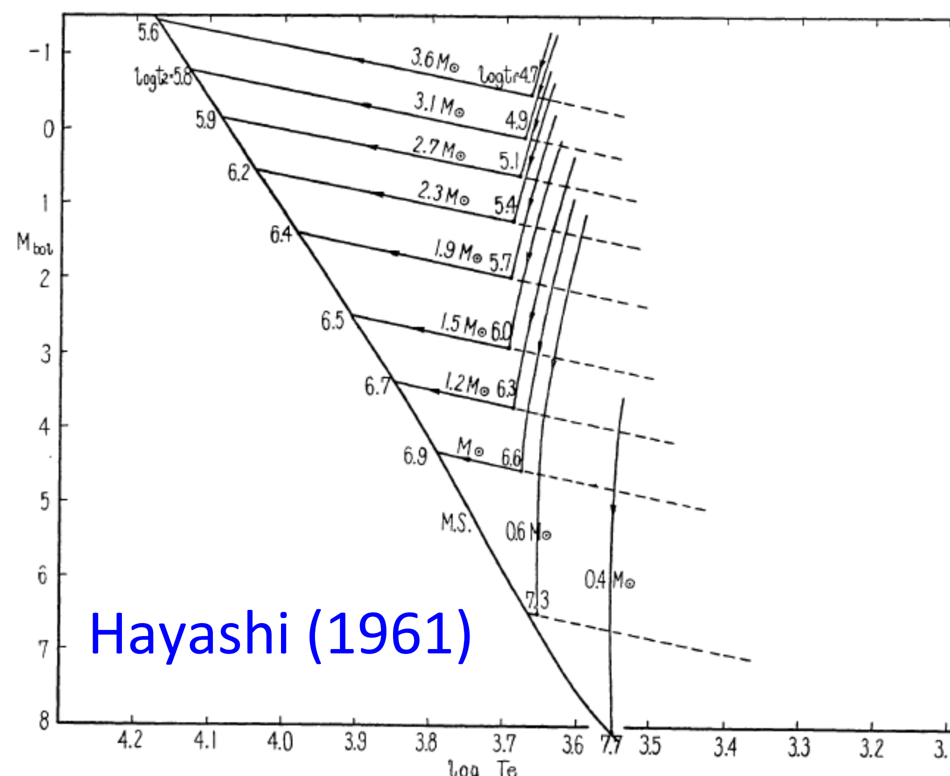
# Hayashi - boundary
# - track
# - phase



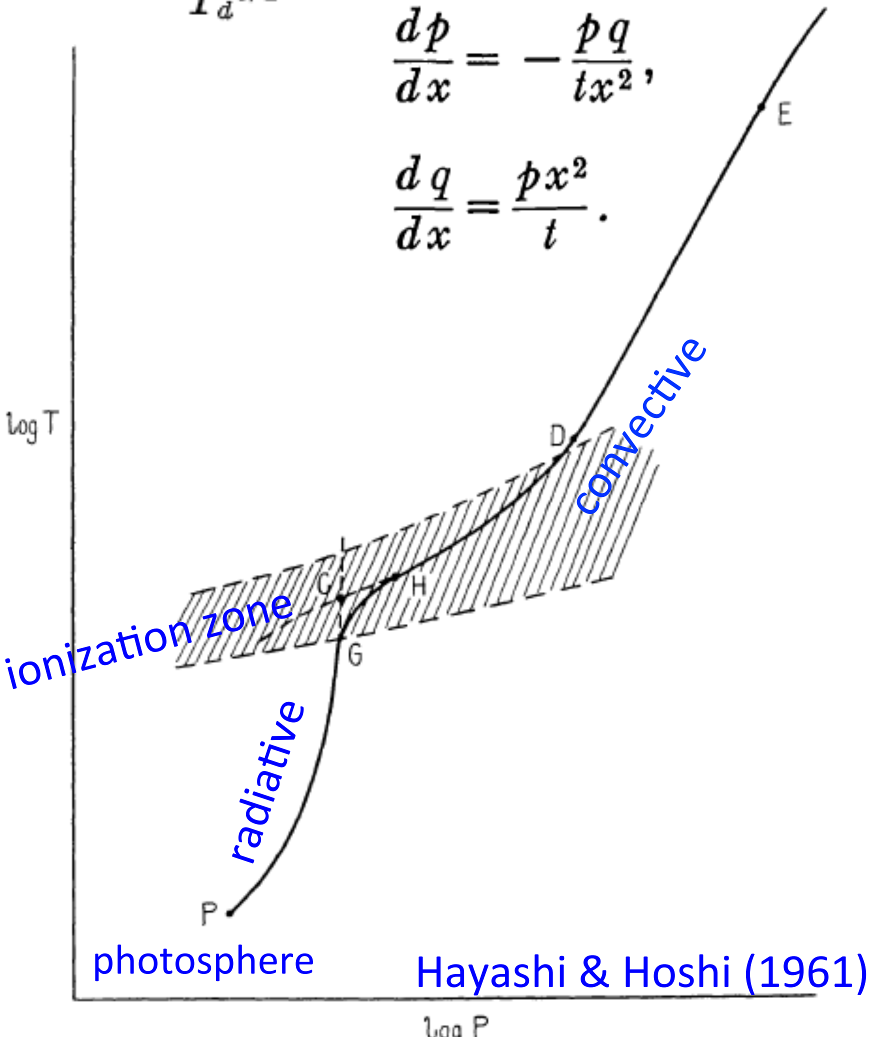



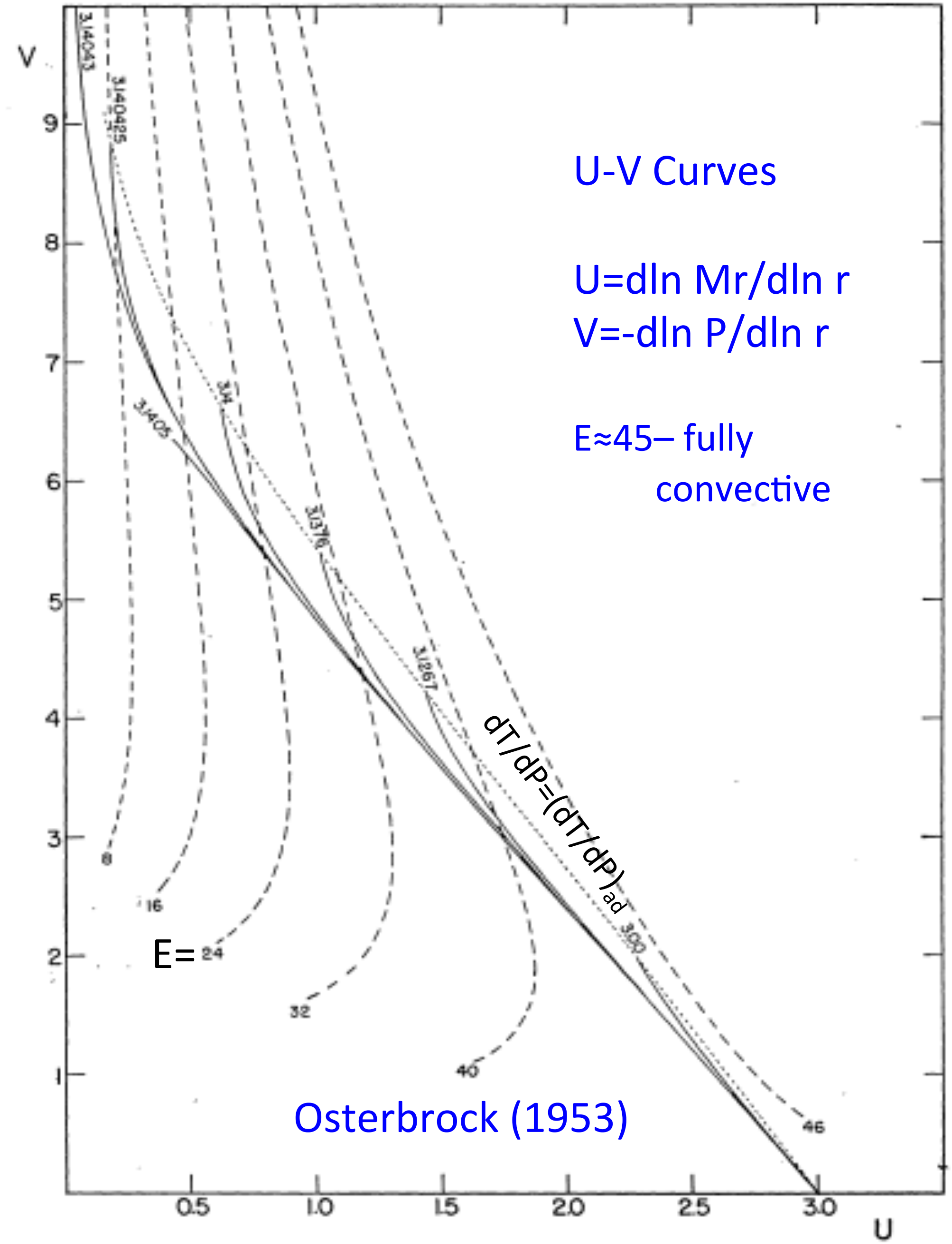
$$E = 4\pi K G^{3/2} (\mu H/k)^{5/2} M^{1/2} R^{3/2}.$$

$$K \equiv \frac{P_d}{T_d^{5/2}} \qquad p = E t^{2.5},$$

$$\frac{dp}{dx} = -\frac{pq}{tx^2},$$

$$\frac{dq}{dx} = \frac{px^2}{t}.$$



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Henyey 法の出現(1964)

# A NEW METHOD OF AUTOMATIC COMPUTATION OF STELLAR EVOLUTION

L. G. Henyey, J. E. Forbes, and N. L. Gould

$$p_{j+1} - p_j + \frac{G m_{j+1/2}(q_{j+1}+q_j)^3(r_{j+1}-r_j)}{(p_{j+1}+p_j)^3(r_{j+1}+r_j)^2} = 0 .$$

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

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

For equation (13):

$$\frac{8}{\pi} m_{j+1/2}'(\xi_{j+1}-\xi_j) - (q_{j+1}+q_j)^3(r_{j+1}+r_j)^2(r_{j+1}-r_j) = 0 .$$

For equation (14):

$$F_{j+1}(\xi_{j+1}+\xi_j)(3\xi_{j+1}-\xi_j) + F_j(\xi_{j+1}+\xi_j)(\xi_{j+1}-3\xi_j)$$
$$- 2 m_{j+1/2}'(\xi_{j+1}-\xi_j)\left[2(\epsilon_{j+1}\epsilon_j)^{1/2} - \frac{E_{j+1}+E_j-E_{j+1}^n-E_j^n}{\Delta t}\right.$$
$$\left. + 3\left(\frac{p_{j+1}+p_j}{q_{j+1}+q_j}\right)^4 \frac{q_{j+1}+q_j-q_{j+1}^n-q_j^n}{\Delta t}\right] = 0 .$$

For equation (15):

$$T_{j+1} - T_j - \frac{(K_{j+1}+K_j)(\xi_{j+1}+\xi_j)^2(F_{j+1}+F_j)(p_{j+1}-p_j)}{m_{j+1/2}} = 0 .$$

For equation (16):

$$E_{j+1} - E_j - 3\left(\frac{p_{j+1}+p_j}{q_{j+1}+q_j}\right)^4 (q_{j+1}-q_j) = 0 .$$

# Pre-main sequence からHe-burning まで自動的に

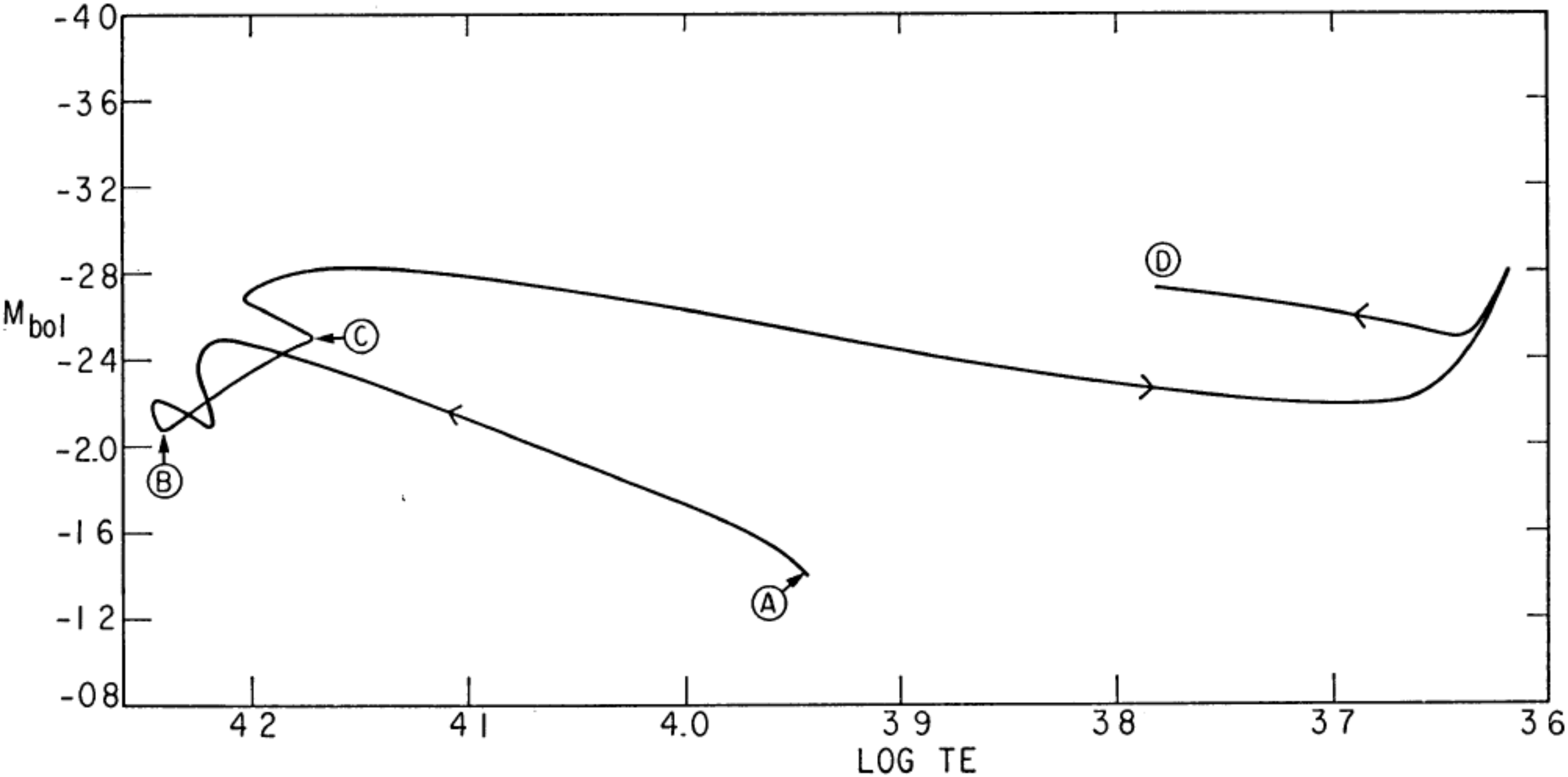
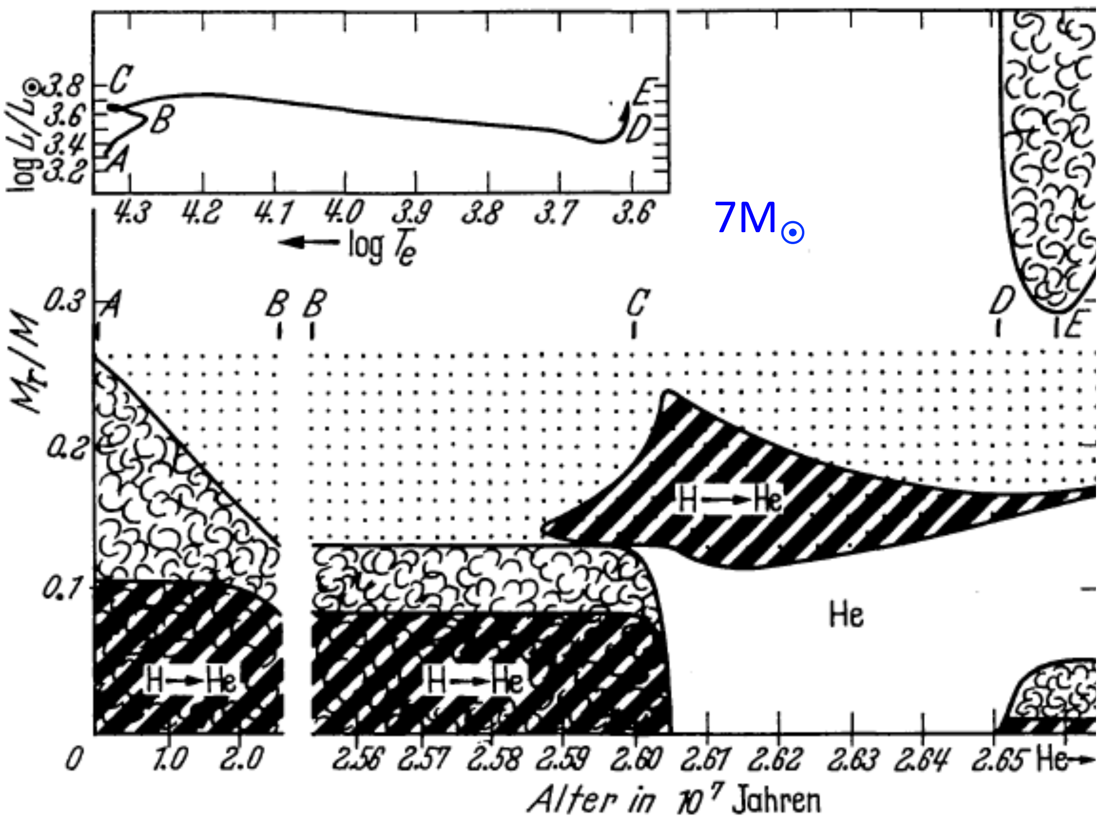



FIG. 1.—The complete evolutionary track in the (log $T_e$, $M_{bol}$) plane computed for 5 $M_\odot$. Indicated

Henyey et al. (1965)

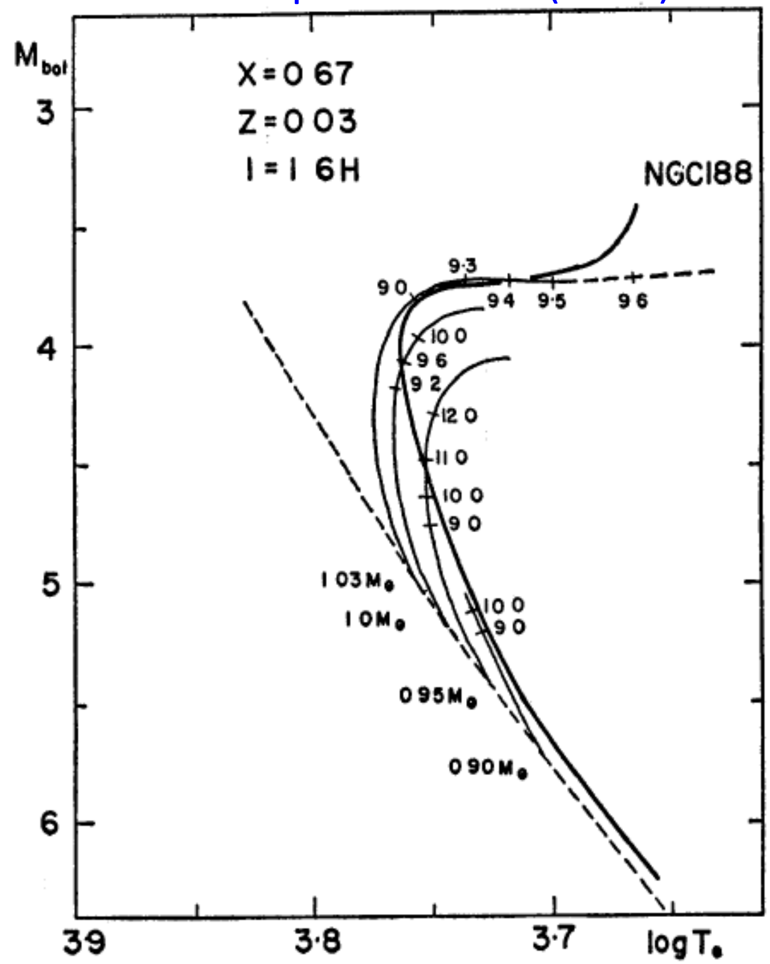
# Henyey 法の出現(1964)

Hofmeister, Kippenhahn & Weigert (1964)

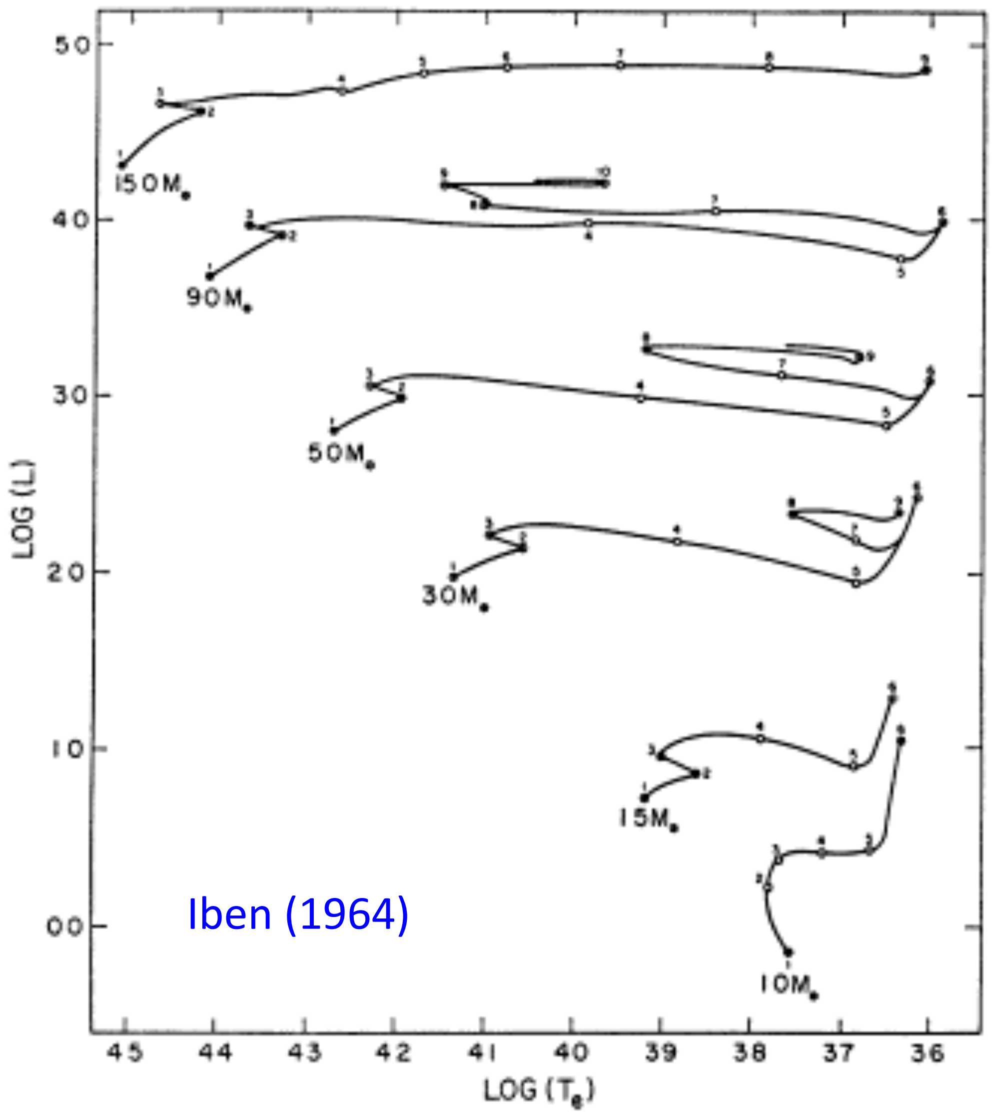



7M⊙

Demarque & Larson (1964)



# Henyey 法の出現(1964)




Iben (1964)

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# He-shell flash (thermal pulse) in AGB stars の発見

THERMAL INSTABILITY IN NON-DEGENERATE STARS

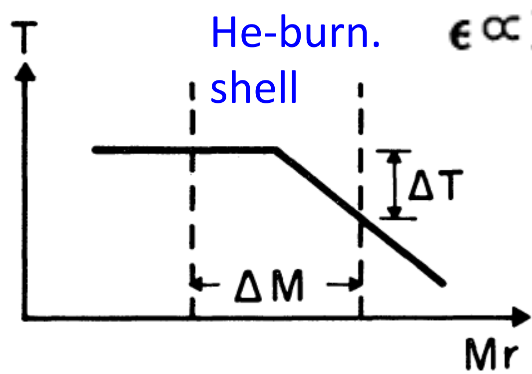
M. Schwarzschild and R. Härm
Princeton University Observatory
*Received May 3, 1965*

In the numerical investigation of the evolution of a star of 1 $M_\odot$ through the phases in which it contains a helium-burning shell as well as a hydrogen-burning shell, an unexpected type of thermal instability has been encountered. This instability is somewhat reminiscent of the helium flash even though

$$\left(\nu - 4\frac{T}{\Delta T}\right)\cdot\frac{\delta T}{T} = \left(\frac{3}{2}\frac{P}{\rho}\frac{\Delta M}{L}\right)\cdot\frac{d}{dt}\,\delta E \quad \longleftarrow \quad \varepsilon - \frac{dL_r}{dM_r} = T\frac{dS}{dt}$$

$$\frac{\delta T}{T} = \frac{3}{5}\left(1 + \frac{2}{5}Q\frac{\Delta r}{r}\right)\cdot\delta E$$

; Hydrostatic adjustment $-8 < Q < -4$
$\Delta r/r \ll 1$ のとき比熱がpositive に




$\epsilon \propto T^\nu$

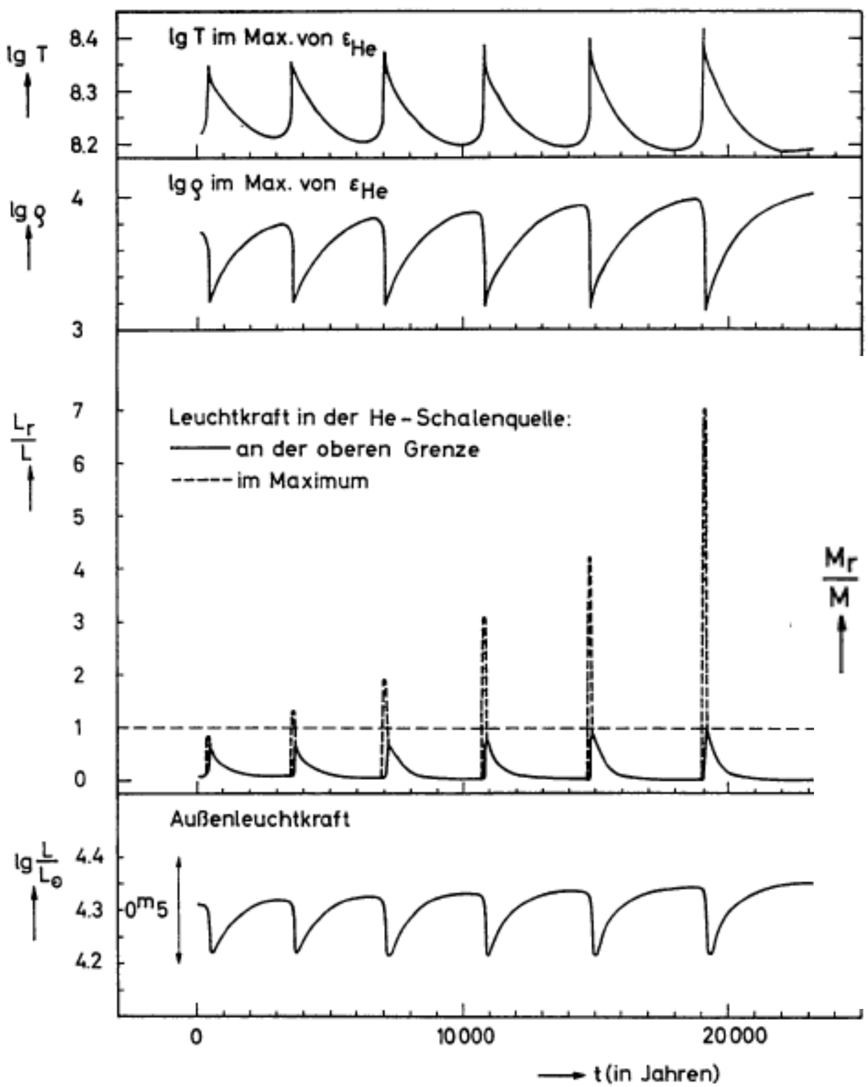
$\nu > 4$ & $\Delta r/r \ll 1$ のときunstable

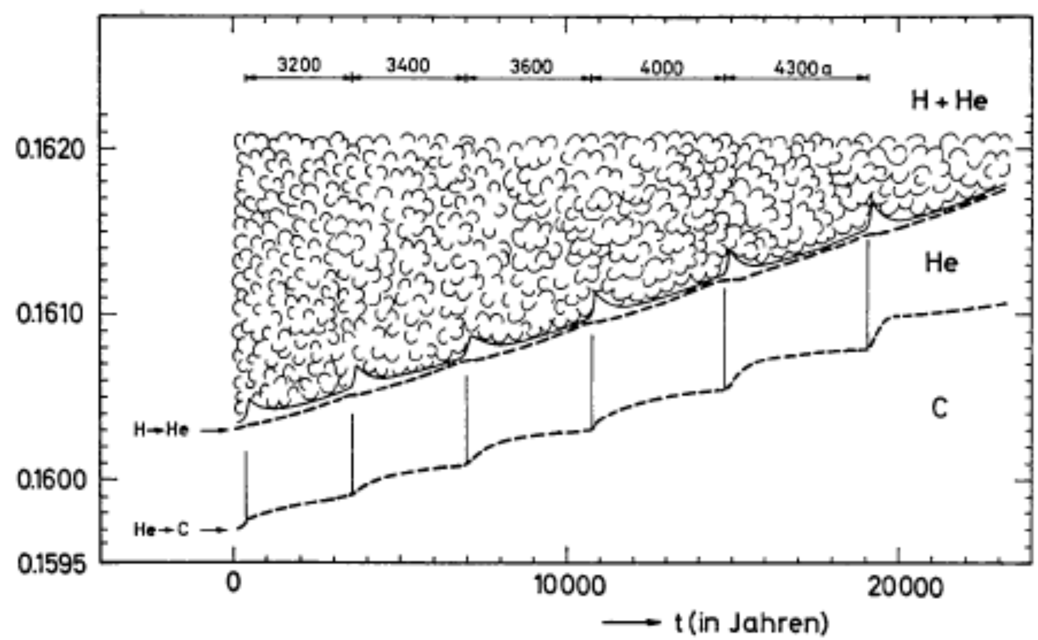
実際はeigen-value problem を解く

$$\delta L_r,\ \delta r,\ \delta P,\ \delta T \propto e^{+t/\tau}$$

# He-shell flashes (thermal pulses)

Weigert (1966) $5M_\odot$



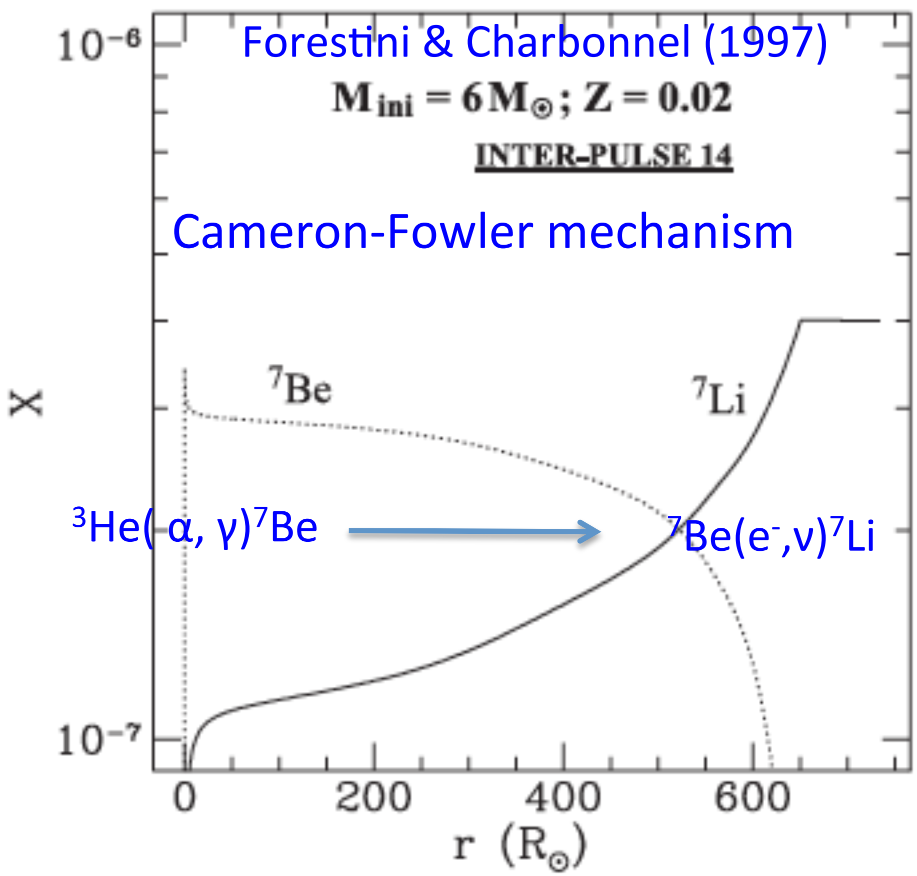



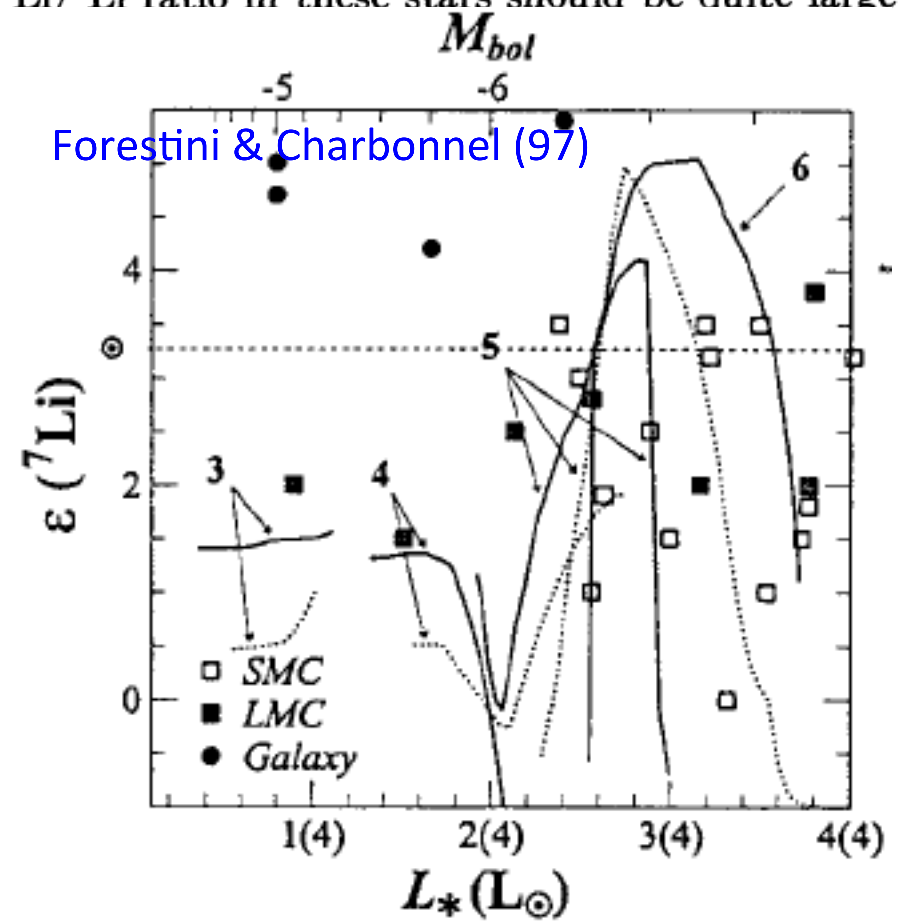
Thermal pulse 2

# LITHIUM AND THE s-PROCESS IN RED-GIANT STARS

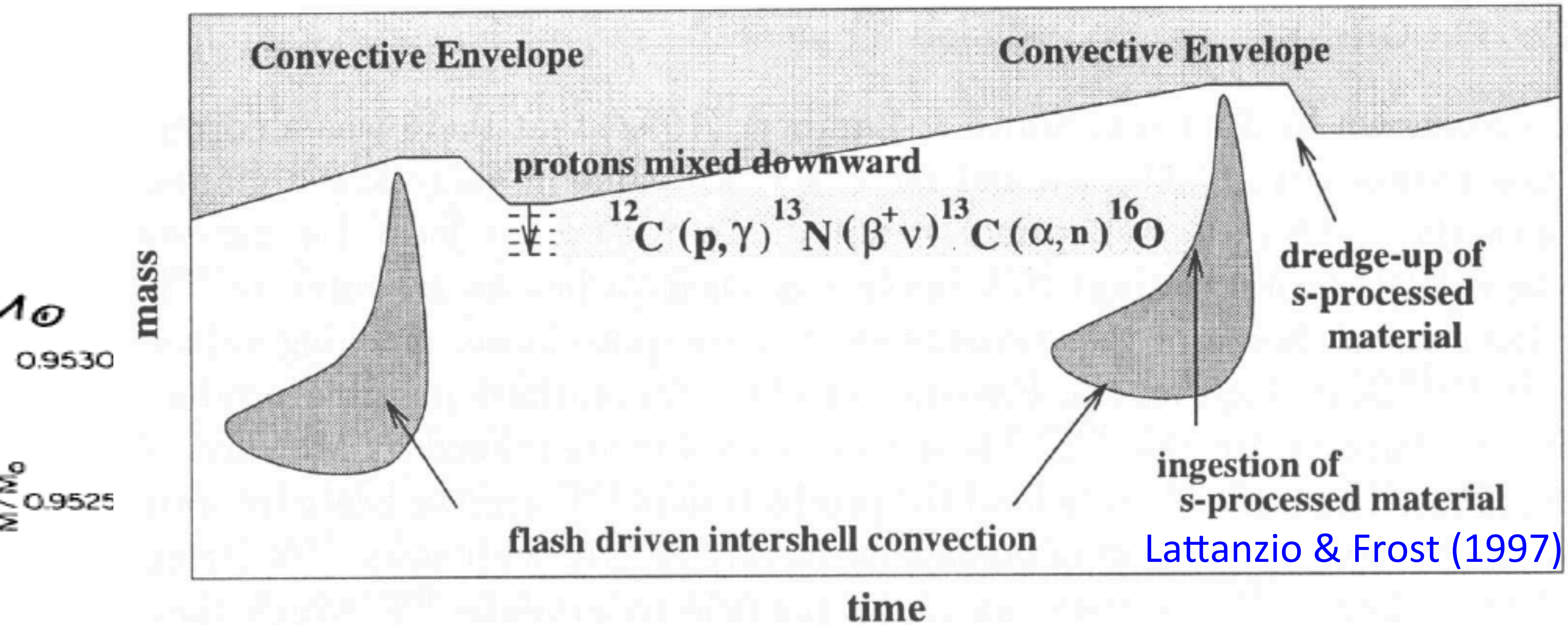
A.G.W.Cameron & W. A. Fowler (1971)

Some consequences are discussed of the possibility that helium-burning shell flashes in advanced stages of stellar evolution occasionally induce complete convection of the outer envelope down to the helium-burning shell. If the hydrogen mixing is relatively small for the first $10^7$ seconds, the result may be the production of large amounts of heavy elements by the s-process. When complete mixing commences, the $^3He$ in the envelope will be converted to $^7Be$, and the subsequent delayed electron capture to form $^7Li$ may allow enough lithium to remain near the surface to account for the very large lithium abundances in some S and carbon red-giant stars. On this basis the $^7Li/^6Li$ ratio in these stars should be quite large (~ 100)

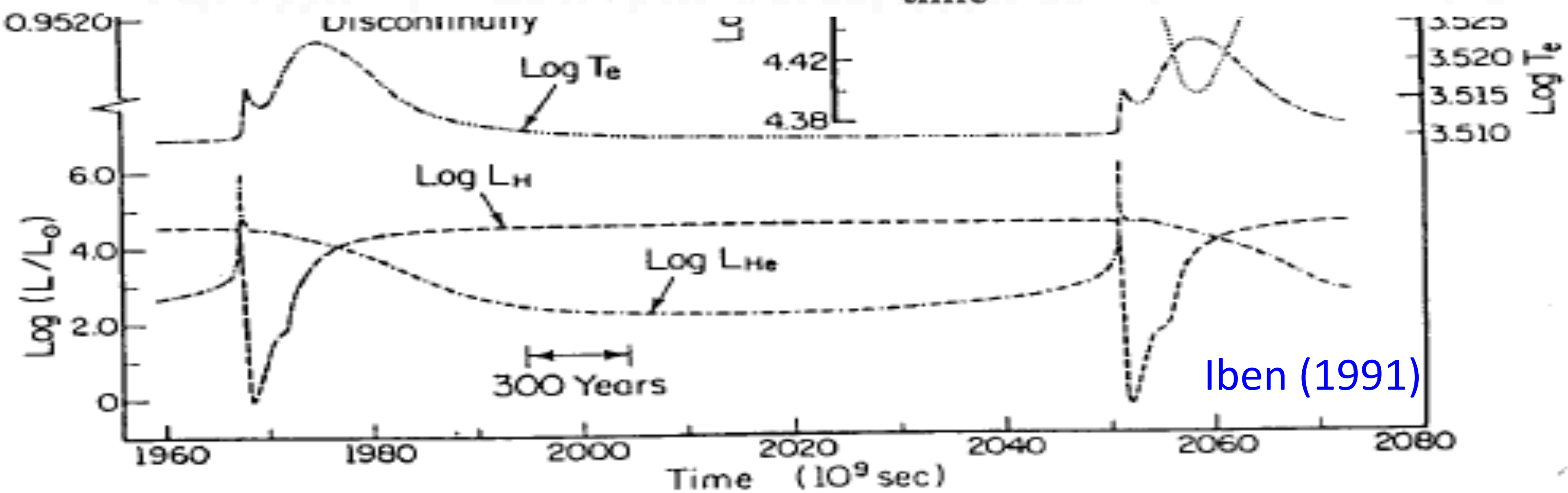


# Third dredge-ups ; Carbon & s-process elements

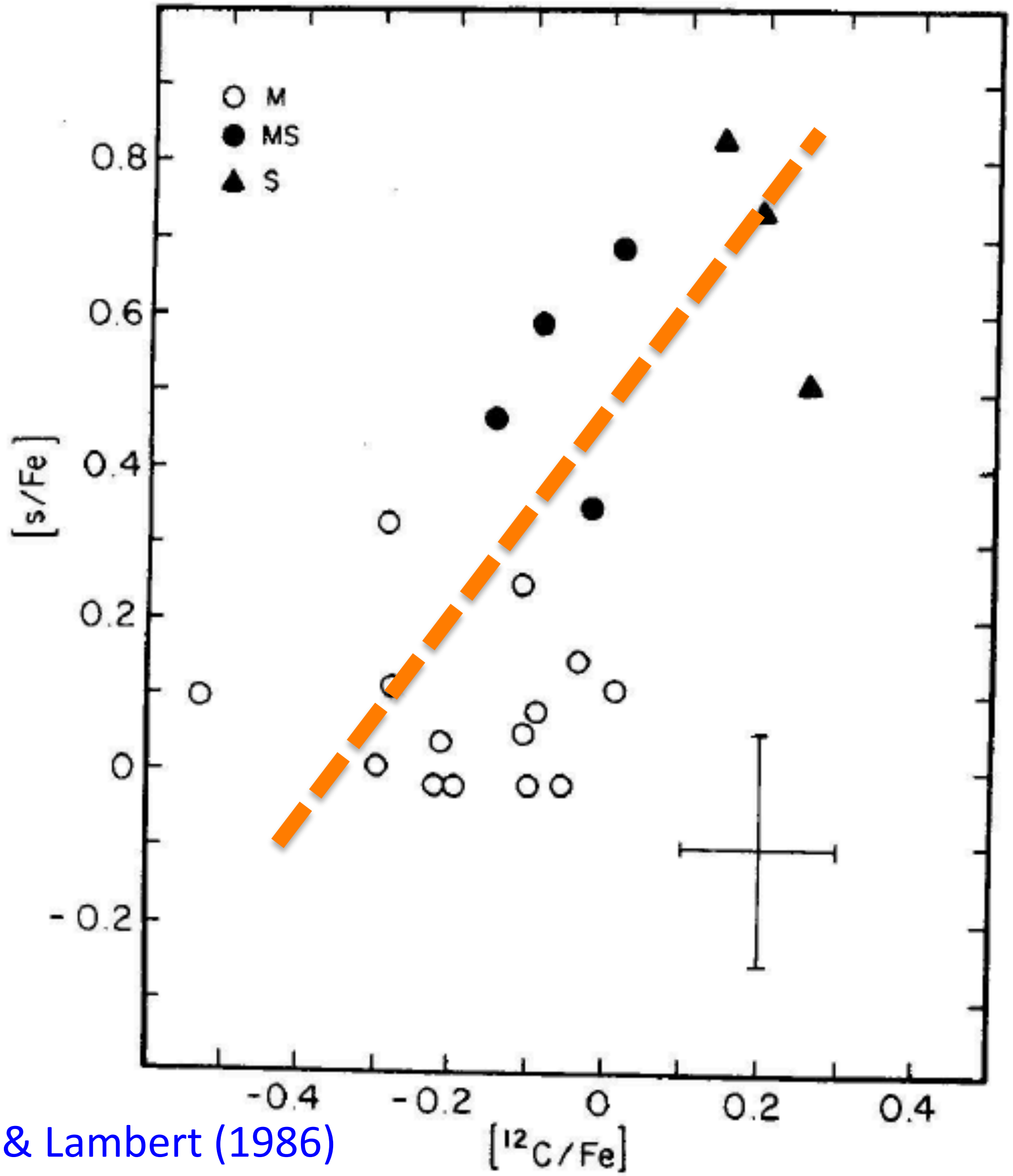



Lattanzio & Frost (1997)




Iben (1991)

# s-process elements と 炭素の増加が 同じprocess – third dredge-ups で




Smith & Lambert (1986)

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# Massive mass-accretion & -stripping in close binary systems and double white dwarf merging

２つの同じような内容の論文が同時に ……

THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 54:335–372, 1984 February

SUPERNOVAE OF TYPE I AS END PRODUCTS OF THE EVOLUTION OF BINARIES WITH COMPONENTS OF MODERATE INITIAL MASS ($M \lesssim 9\ M_{\odot}$)[1]

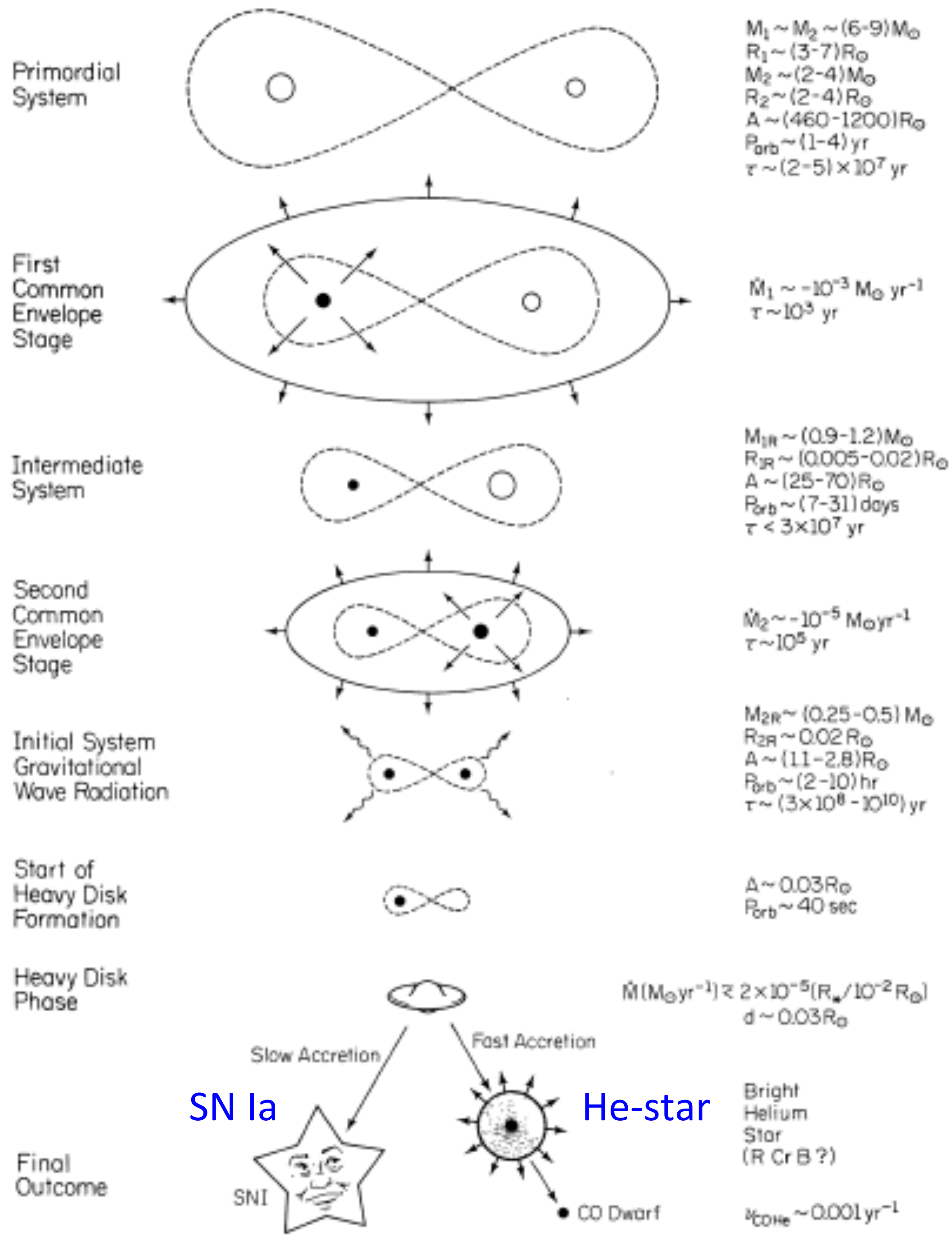
ICKO IBEN, JR., AND ALEXANDER V. TUTUKOV[2]
University of Illinois at Champaign-Urbana
*Received 1983 June 20; accepted 1983 September 15*

THE ASTROPHYSICAL JOURNAL, **277**:355–360, 1984 February 1

DOUBLE WHITE DWARFS AS PROGENITORS OF R CORONAE BOREALIS STARS AND TYPE I SUPERNOVAE[1]

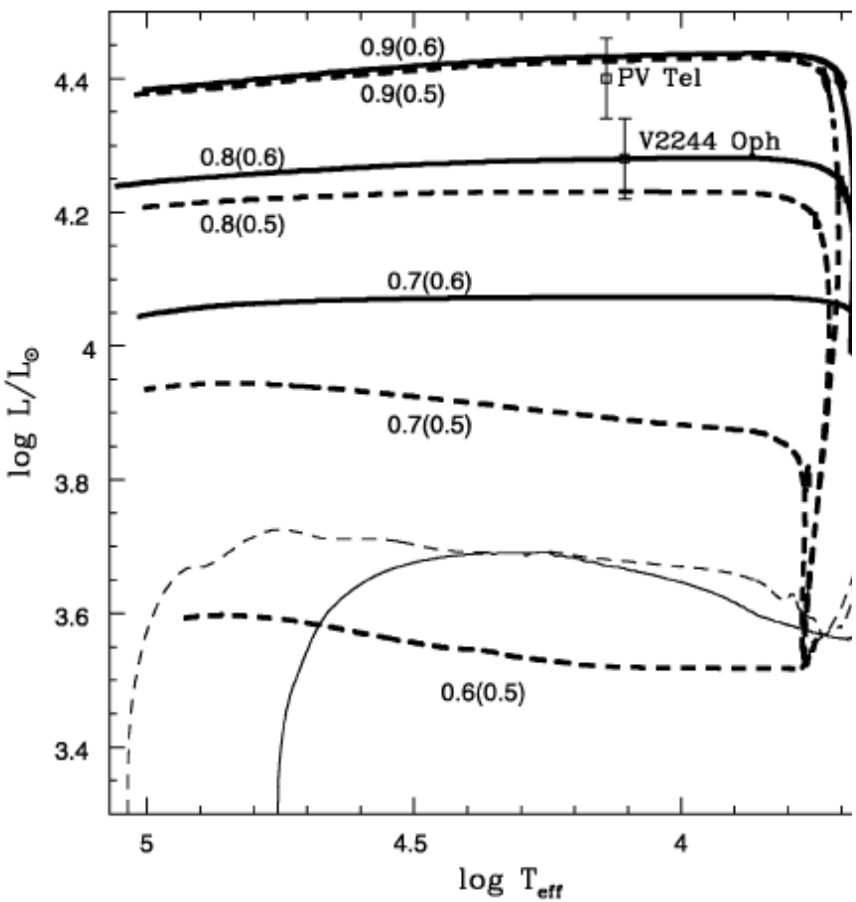
R. F. WEBBINK
Department of Astronomy, University of Illinois
*Received 1983 June 13; accepted 1983 July 27*

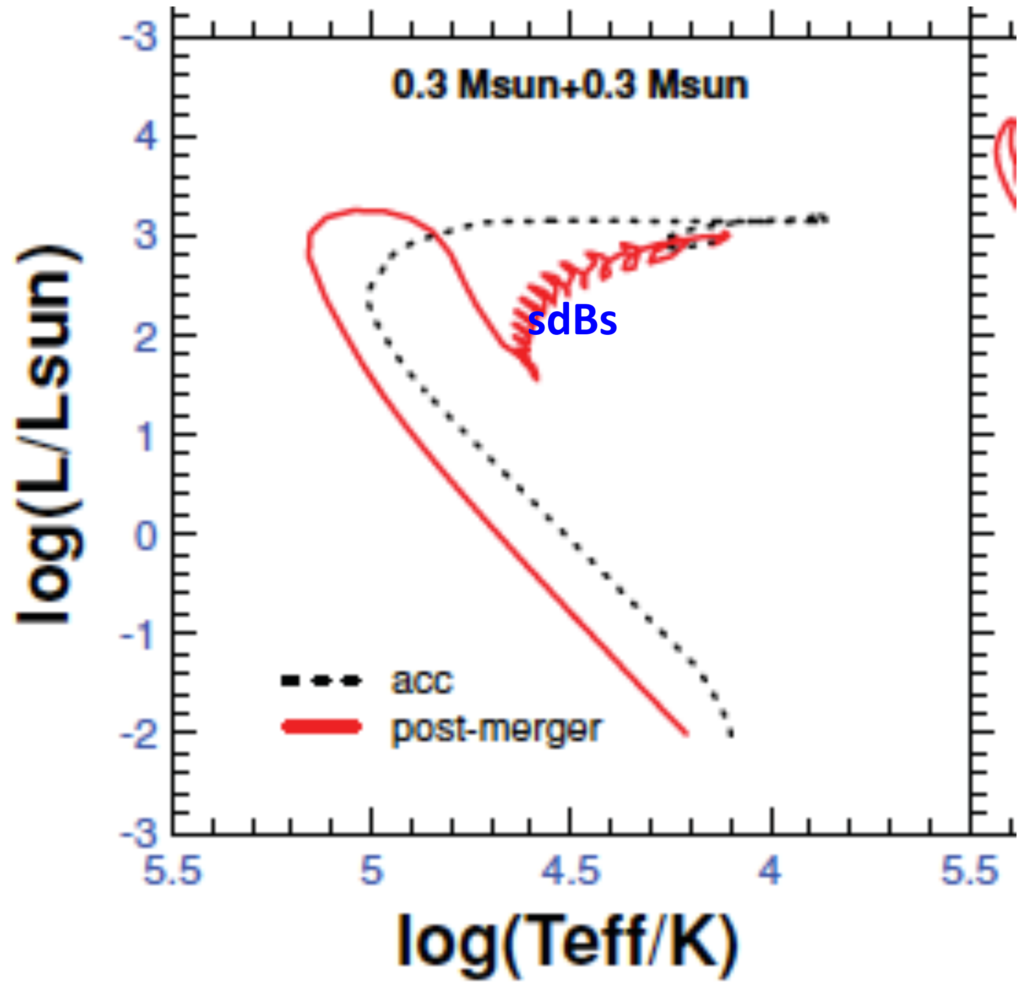
IBEN AND TUTUKOV



# DWD mergers

## massive → luminous Hds; low mass → He-rich sdBs




Zhang & Jeffery (2011)

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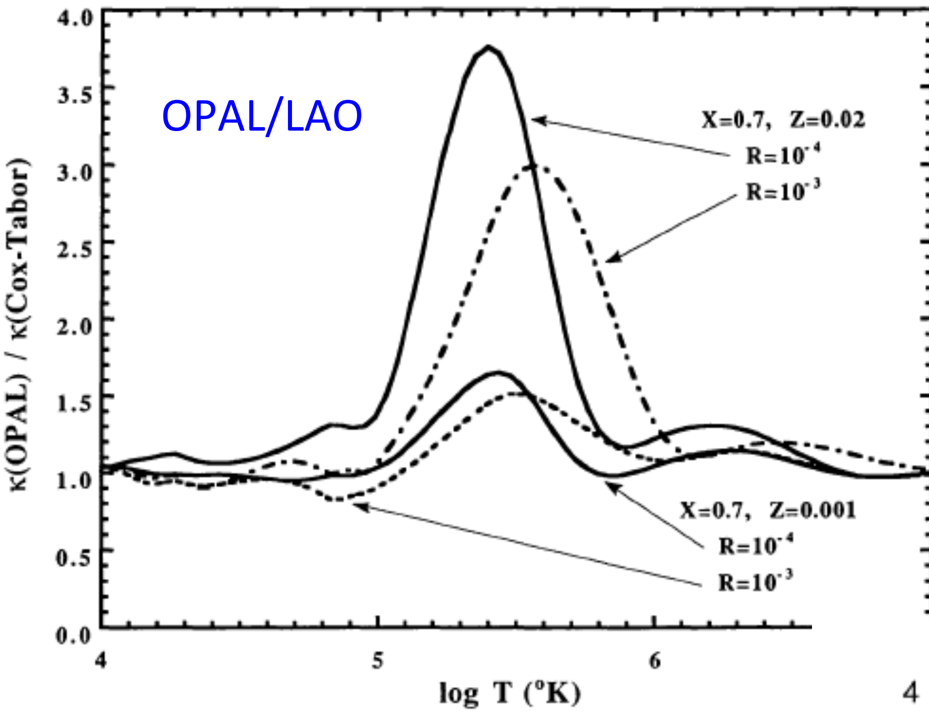
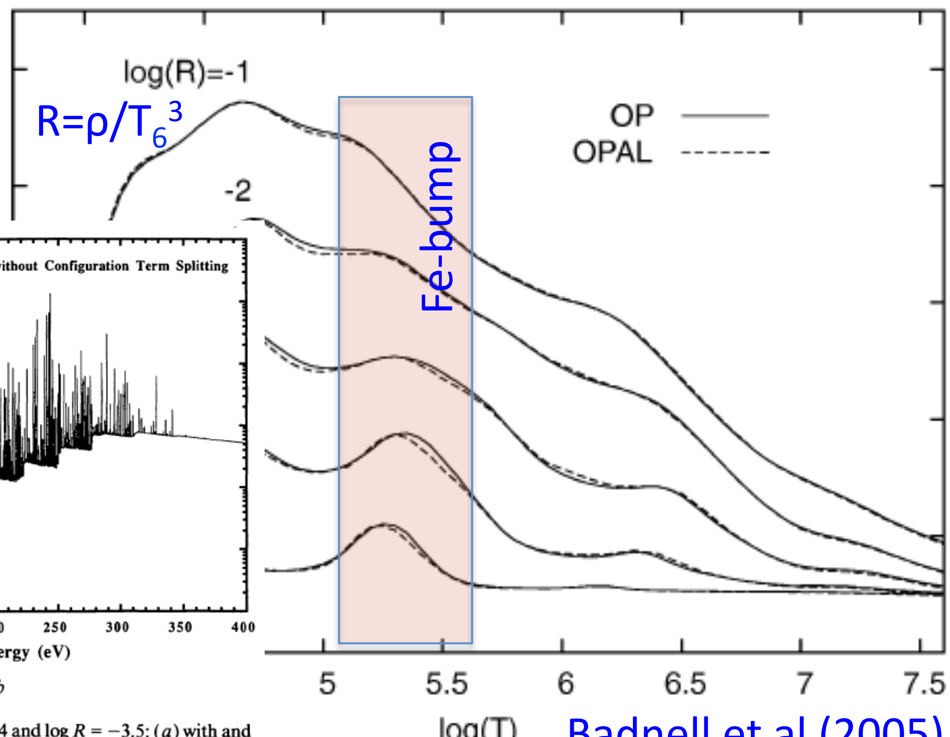
# New opacity tables の出現

## OPAL & OP

## 1992 1994

Fe-bump was missing in old opacities




Badnell et al (2005)

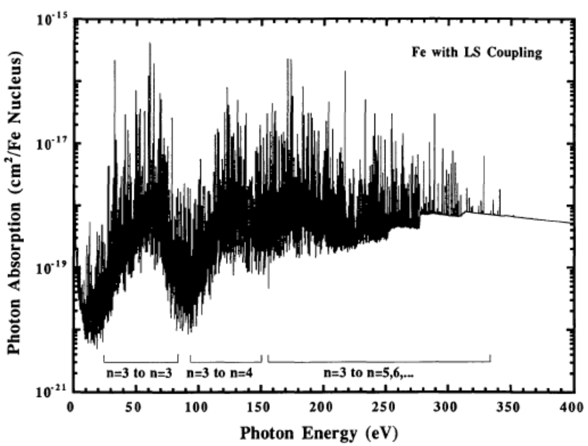



FIG. 22*a*

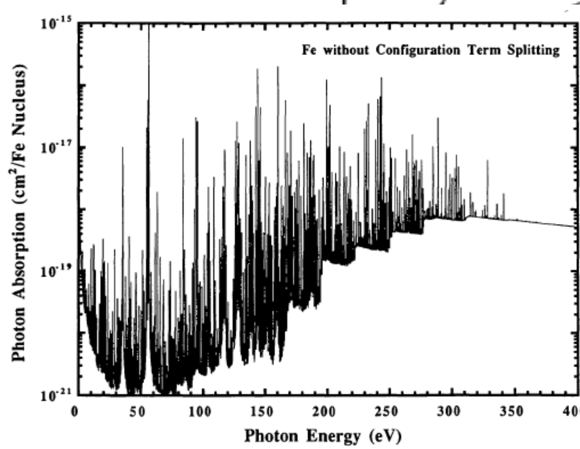
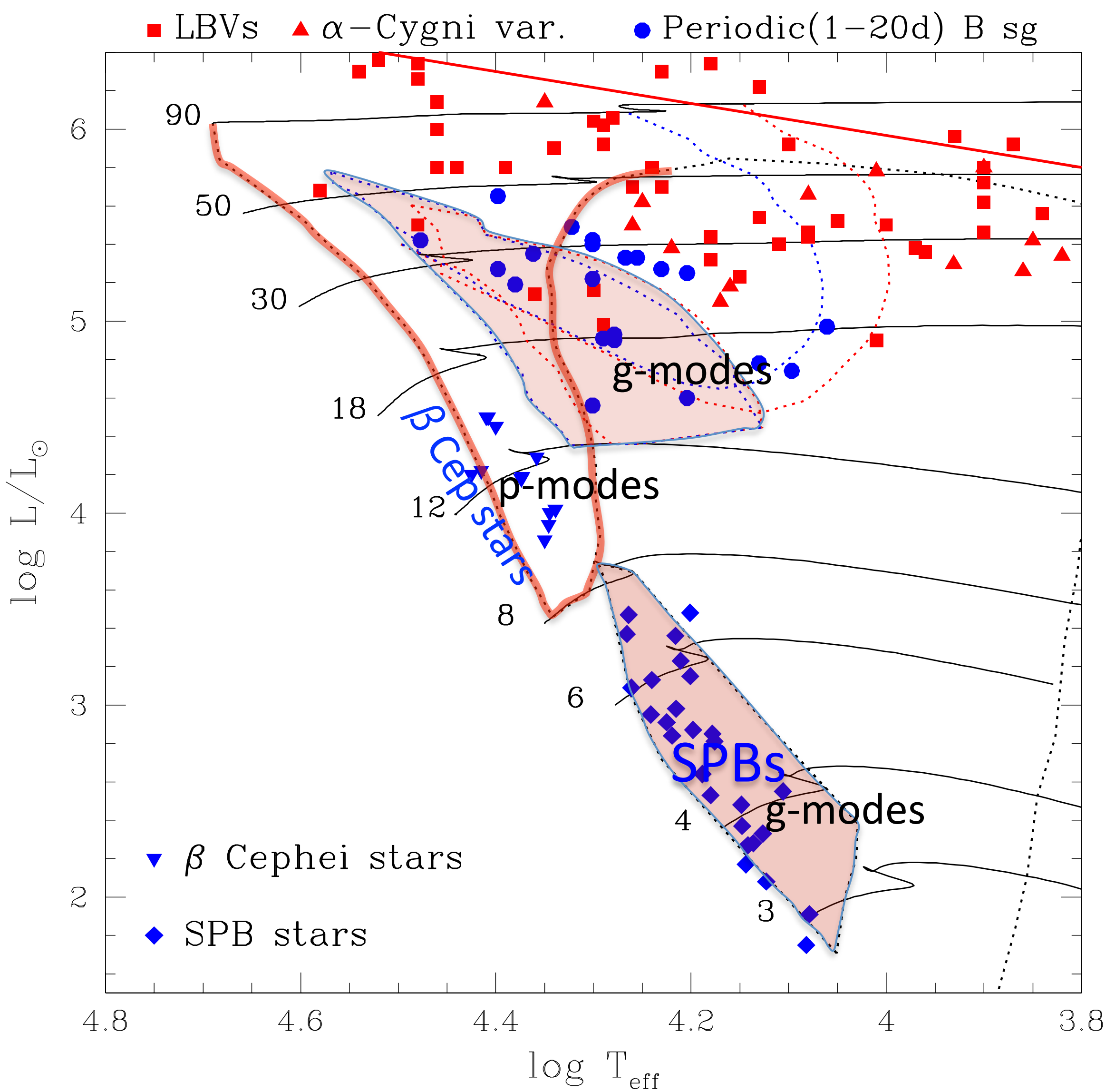



FIG. 22*b*

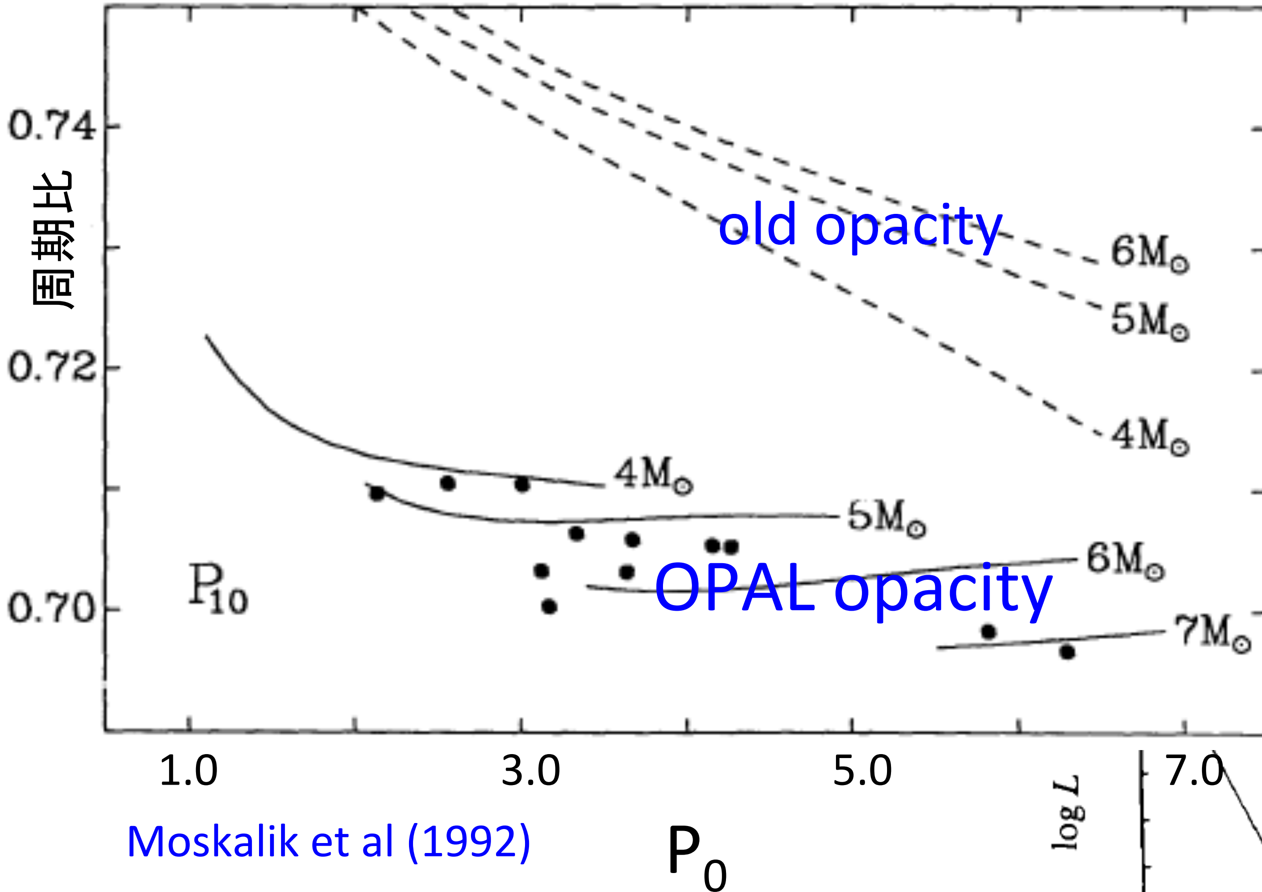
FIG. 22.—Iron frequency-dependent photon absorption for $X = 0.7$, $Z = 0.02$, and CT metal abundances at $\log T = 5.4$ and $\log R = -3.5$: (*a*) with and (*b*) without configuration term splitting. Initial and final principal quantum number for the optically active electron is denoted by $n$.

OPAL & OP opacities の出現

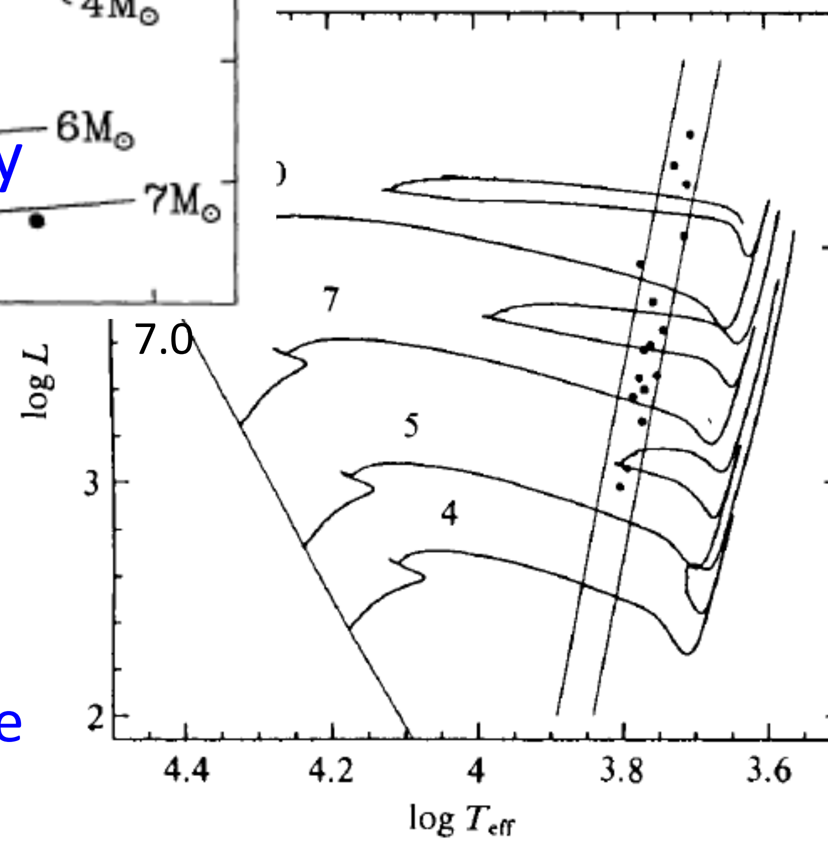
# Fe-bump of opacity excites pulsations in B-type stars



# New opacity solved mass discrepancy of Cepheids



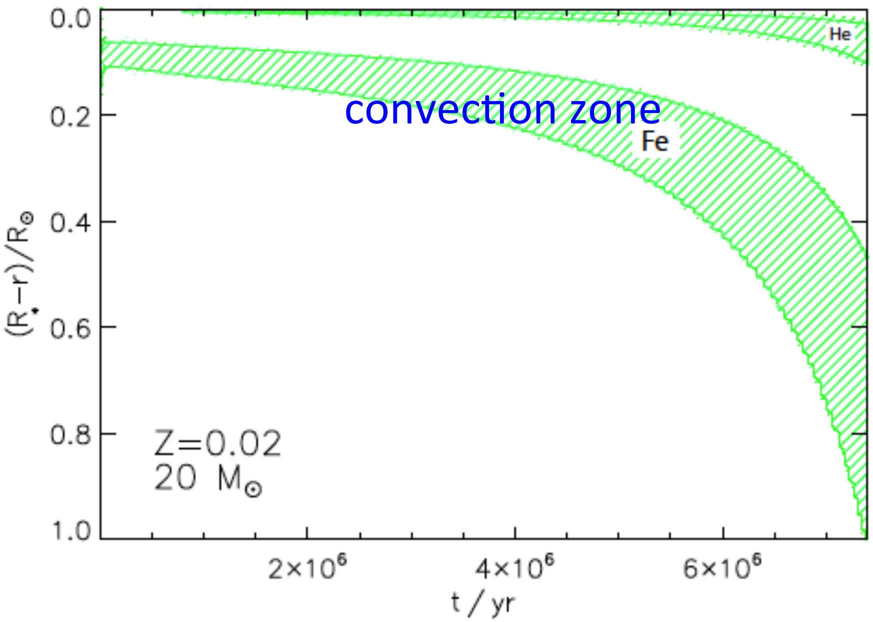

Moskalik et al (1992)

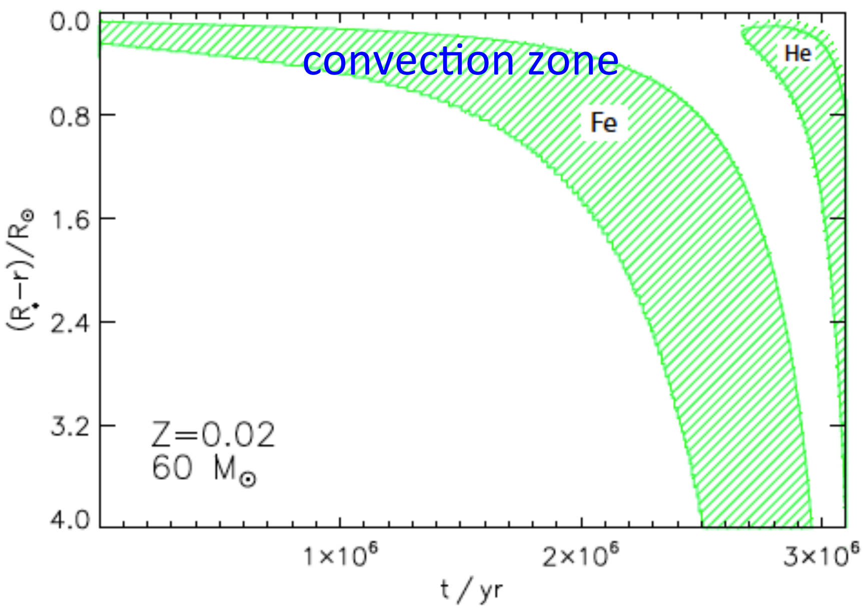


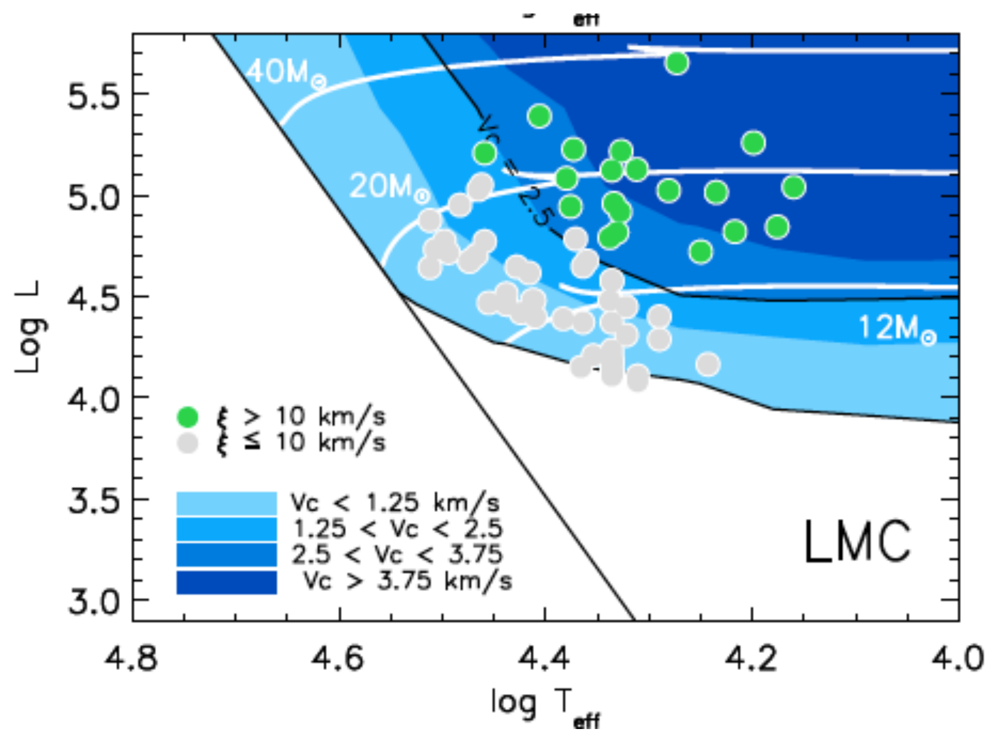

$P_i = f_i(M,R)$ $i=0$ fundamental mode

$=1$ first overtone mode

# Fe opacity bump produces convection zones in the envelopes of hot massive stars




Cantaillo et al. (2009)

# 未解決の問題点

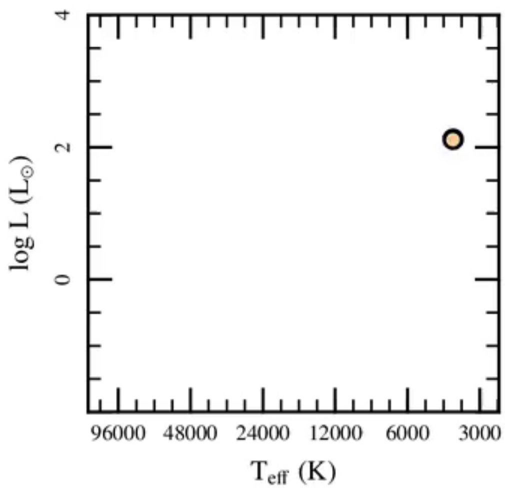
- mixing length/convection models
- microscopic diffusions with weak winds/ turbulence/pulsations
- Mixing in radiative layers
  - Convective core overshooting
  - Evolution of Ω(r)
  - Rotational mixing
- Wind mass loss from supergiant stars
- Evolutions in stellar mergers

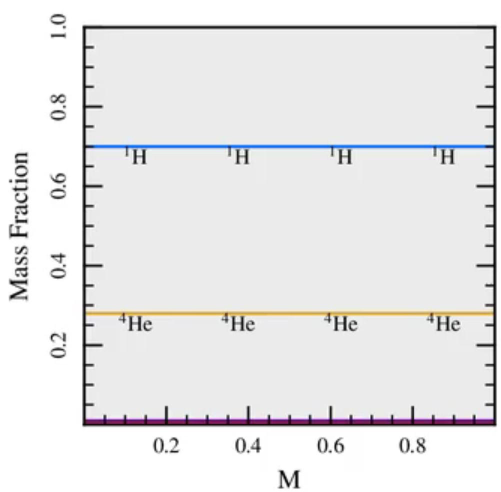
# A revolution?

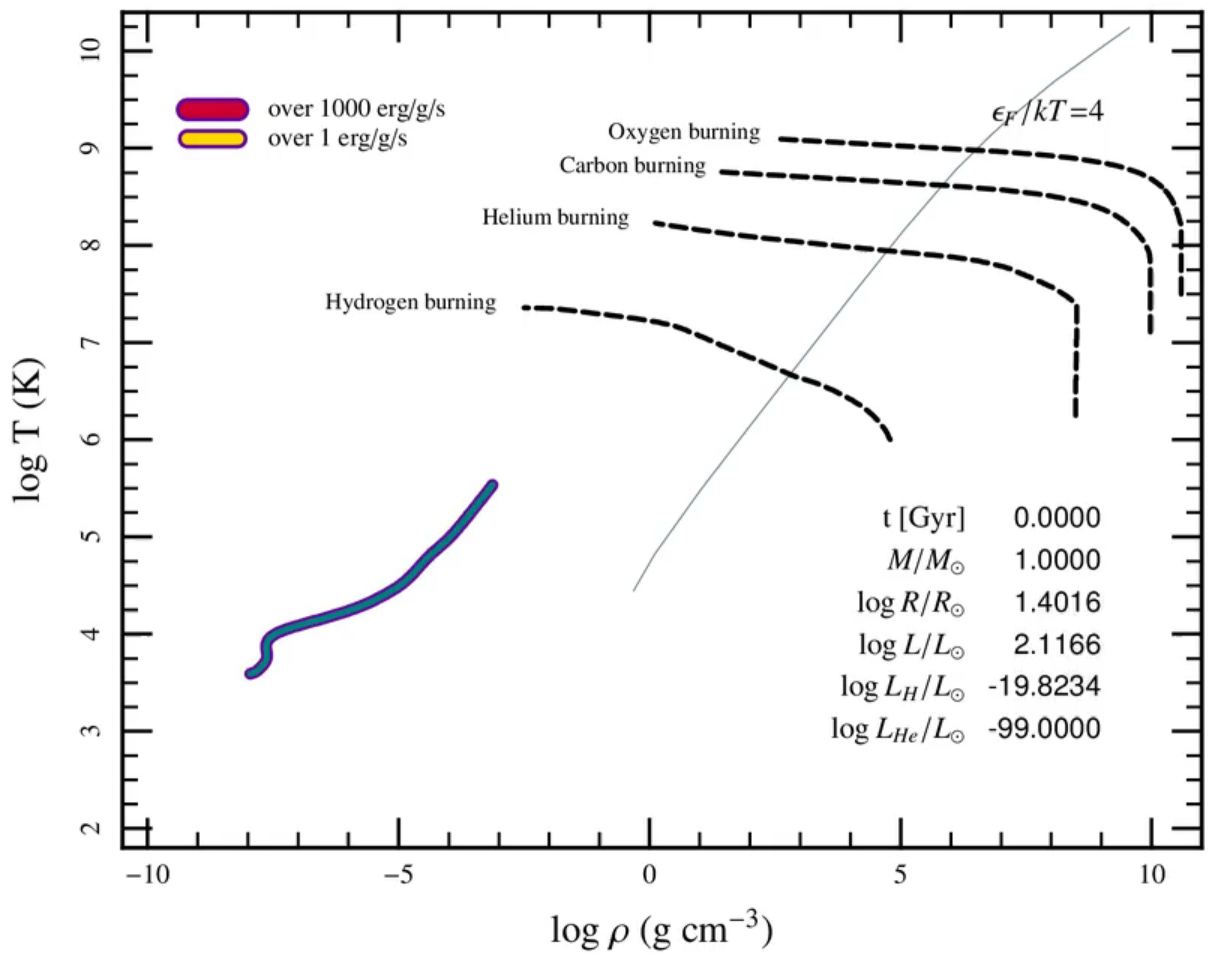
# MESA

**Modules for Experiments in Stellar Astrophysics**

Paxton et al (2011)




produced by Josiah Schwab