# UTAP 論文ゼミ

21/July/2015　細川 隆史

- “A Polytropic Model of an Accretion Disk, a Boundary Layer, and a Star”

  B.P. Paczynski (1991), ApJ, 370, 597

- “On the Role of the ΩΓ Limit in the Formation of Pop III Massive Stars”

  H. Lee, & S.C. Yoon (2015), submitted to ApJ (not appeared yet)

A request for reviewing came one day….

## On the Role of the ΩΓ Limit in the Formation of Population III Massive Stars

Hunchul Lee
akaialee@astro.snu.ac.kr

Sung-Chul Yoon
yoon@astro.snu.ac.kr

*Department of Physics and Astronomy, Seoul National University, Gwanak-gu, Gwanak-ro 1, 151-742, Seoul, Korea*

### ABSTRACT

We explore the role of the modified Eddington limit due to rapid rotation (the so-called ΩΓ−limit) in the formation of Population III stars, using one-dimensinoal stellar evolution simulations of mass-accreting zero-metallicity protostars at a very high rate ($\dot{M} \sim 10^{-3}$ $M_\odot$ $yr^{-1}$). The protostar would reach the Keplerian rotation very soon after the onset of mass accretion, but it could continue mass accretion as stellar angular momentum is transferred outward to the accretion disk by viscous stress. As the accreting protostar evolves, the envelope expands rapidly when the stellar mass reaches $5 \sim 7$ $M_\odot$ and the corresponding Eddington factor sharply increases. Reaching the ΩΓ−limit in this way, further mass accrection would be significantly slowed down, limiting the mass at the zero-age main sequence to about 20 $M_\odot$. Although our analysis is based on Pop III protostar models, this role of the ΩΓ−limit in limiting the initial mass would be universal in the formation process of massive stars with rapid mass accretion, regardless of metallicity.

*Subject headings:* cosmology: early universe — stars: evolution — stars: formation — stars: Population III – stars : rotation

20$M_\odot$以上のPopIII星は作れない？

# Paczynski 91 概要

目的: 円盤を通して質量降着する星を考える。
星の回転が小さければ、massとともに角運動量も
持ち込まれる。

しかし、星が持てる角運動量には限界がある (Ω限界)

Ω限界に近い星にさらにaccretionさせたらどうなる
のだろうか？そもそも可能か？

手法: 円盤、星、遷移層を合わせた定常解を解析的に求める。

結論: Ω限界に近くても降着は可能
massは星に流入し、角運動量は抜かれる解に移行する。

# Paczynski (1)

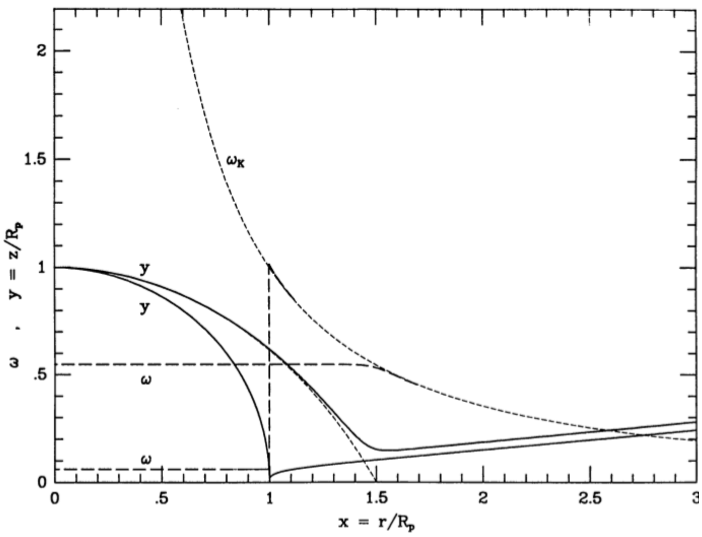



TABLE 1

PARAMETERS FOR SELECTED MODELS

| Model | $j/j_{cr}$ | $\Omega_s/\Omega_{cr}$ | $R_e/R_p$ |
|---|---|---|---|
| 1......... | 1.8647 | 0.1111 | 1.0018 |
| 2......... | 2.0014 | 0.8273 | 1.1571 |
| 3......... | 2.0986 | 0.9468 | 1.2757 |
| 4......... | 2.1621 | 0.9827 | 1.3595 |
| 5......... | 2.1981 | 0.9942 | 1.4148 |
| 6......... | 2.2126 | 0.9980 | 1.4521 |
| 7......... | 2.1843 | 1.0010 | ... |
| 8......... | 2.2145 | 0.9991 | 1.4653 |
| 9......... | 2.2045 | 1.0003 | ... |
| 10........ | 2.1311 | 1.0018 | ... |
| 11......... | 1.8371 | 1.0035 | ... |
| 12......... | 1.1023 | 1.0052 | ... |
| 13......... | 0.0000 | 1.0066 | ... |
| 14......... | −1.8371 | 1.0081 | ... |

Model #1: slowly rotating star, accreting mass, and angular momentum
Model #13: rapidly rotating star, accreting mass, but no angular momentum

# Paczynski (2)

Cases for slowly rotating stars (mostly Ωs < Ωcr)

z-r profile (disk-star surface)　　角速度profile

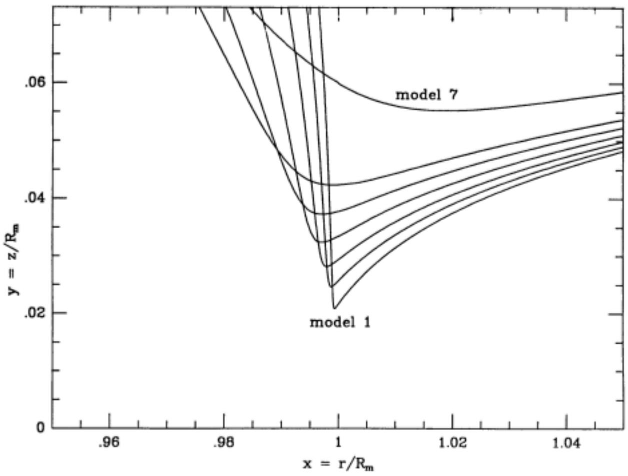



FIG. 2a

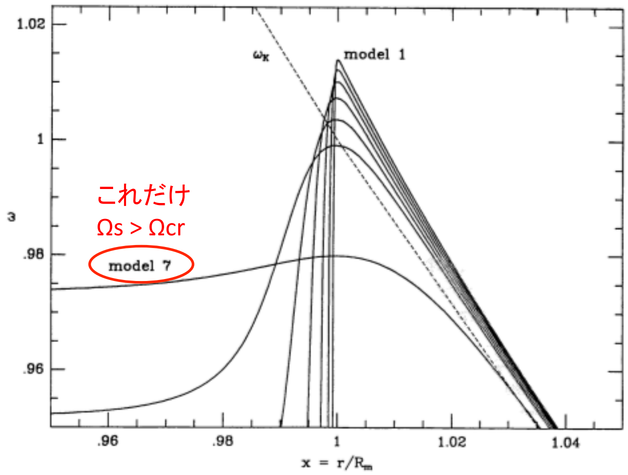



FIG. 2b

FIG. 2.—(*a*) A small region near the boundary layer is shown for models 1–7. The surface of the star–boundary layer–disk system is shown with solid lines. Model 7 rotates with a supercritical angular velocity. The unit length, $R_m$, corresponds to the radius at which angular velocity reaches the maximum, at which the "no torque boundary condition" can be applied. (*b*) The variation of angular velocity with radius is shown for models 1–7 by solid lines. The Keplerian angular velocity is shown with a broken line. The unit of length, $R_m$, corresponds to the radius at which angular velocity reaches its maximum, at which "no torque boundary condition" can be applied.

# Paczynski (3)

Cases for rapidly rotating stars (mostly Ωs > Ωcr)

z-r profile (disk-star surface)　　角速度profile

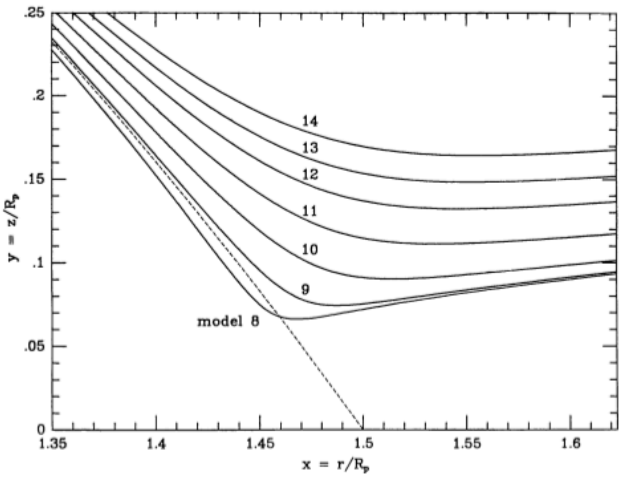



FIG. 3a

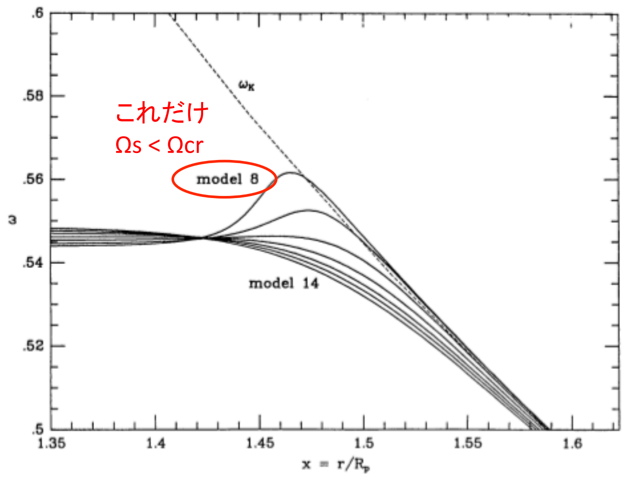



FIG. 3b

FIG. 3.—(*a*) A small region near the boundary layer is shown for models 8–14. The surface of the star–boundary layer–disk system is shown with solid lines. Models 9–14 rotate with supercritical angular velocity. Model 13 accretes matter but no angular momentum. Model 14 accretes matter and loses angular momentum to the disk through viscous stresses. The dashed line corresponds to the surface of an isolated star rotating with the critical angular velocity; it has a cusp at the equator. The unit of length is the polar radius of the star, $R_p$. (*b*) The variation of angular velocity with radius is shown for models 8–14 by solid lines. The Keplerian angular velocity is shown with a broken line. The unit of length is the polar radius of the star, $R_p$.

# Lee & Yoon 15 概要

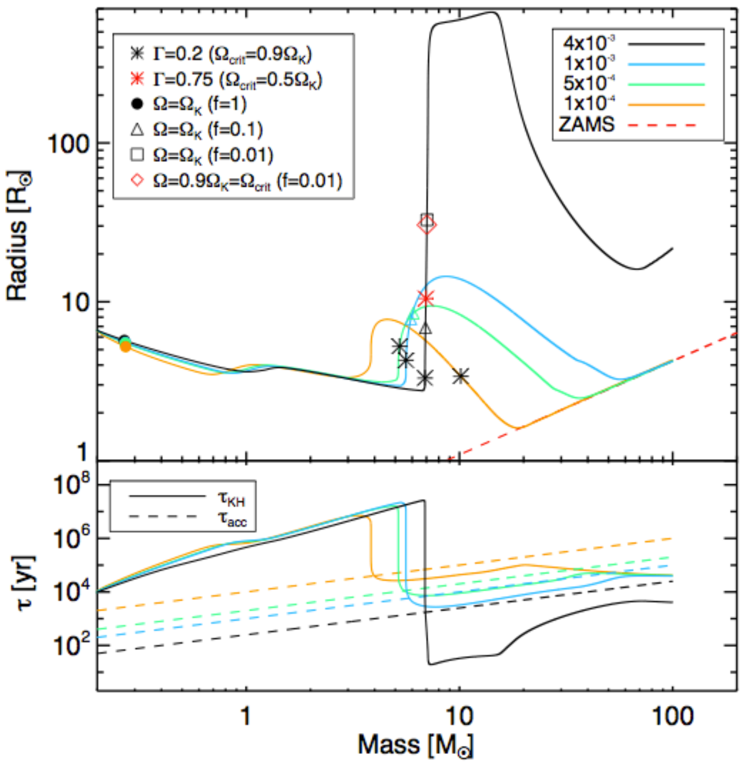
目的: 星光度がEddingon値に近い場合は、輻射圧の寄与のため、$\Omega_s < \Omega_K$でも星構造を維持できない ($\Omega\Gamma$限界)
これでは星から角運動量を抜けないので、
降着が不可能になるであろう。

初代星形成時にこのようになる場合があるか？
どれくらい効くだろうか？

手法: 降着ありの原始星進化計算 (with MESA code)

結論: 降着率が大きめだと容易にこの限界に達する。
その結果、ZAMS到達時の星質量は$20M_\odot$以下。

# Lee & Yoon (1)




様々な一定降着率下での原始星(半径)の進化

timescale比較

- Accretion time

$$t_{\rm acc} \equiv \frac{M_*}{\dot{M}_*}$$

- Kelvin-Helmholtz time

$$t_{\rm KH} \equiv \frac{GM_*^2}{R_* L_*}$$

# Lee & Yoon (2)

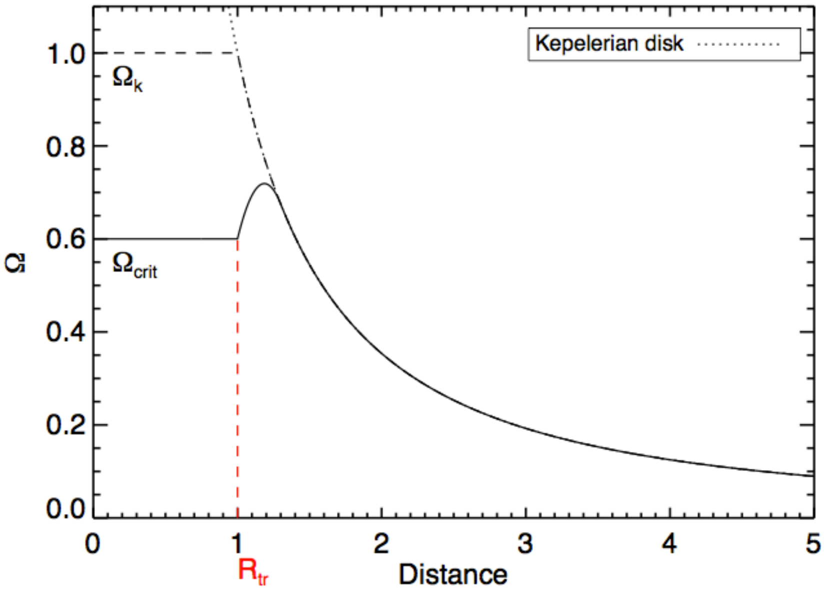
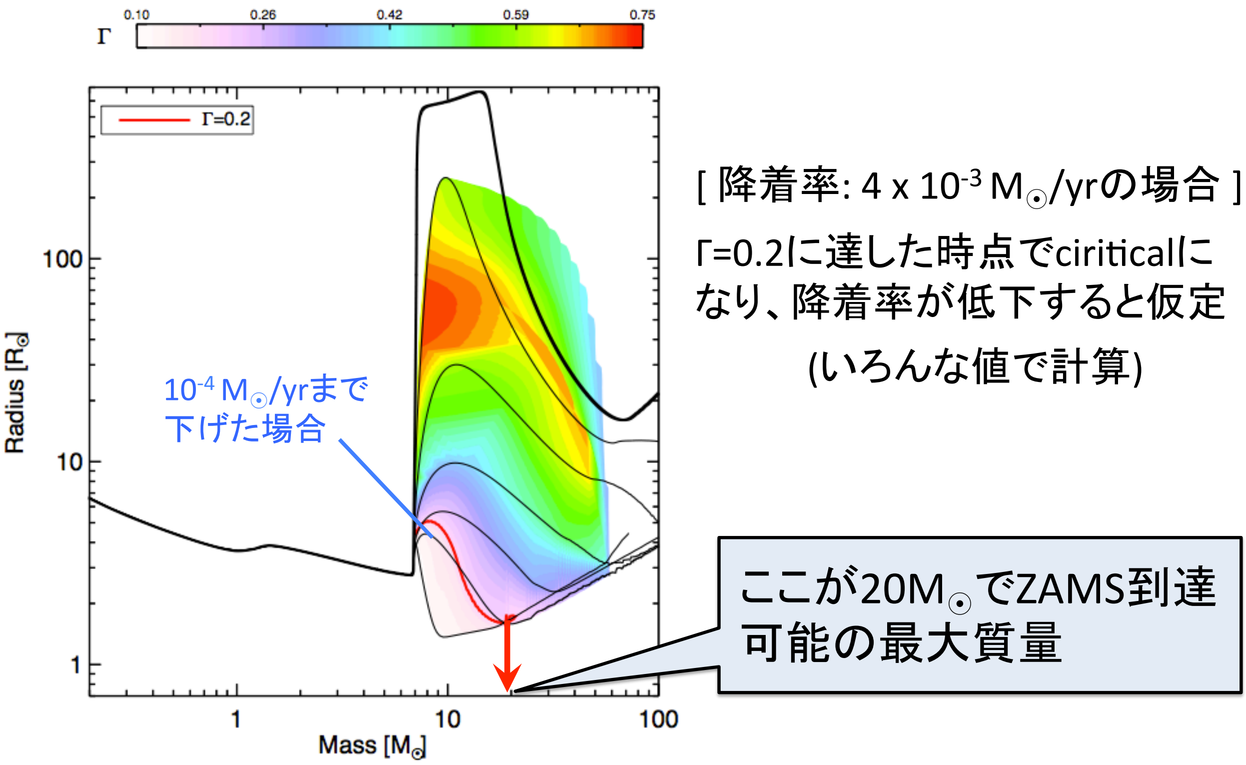



Fig. 4.— Illustration for the rotation profile of a critically rotating protostar accreting matter via the Keplerian disk when the Eddington factor is considered (solid line) and not considered (dashed line). Note that x-axis and y-axis values are scaled so that Ω reaches 1 at $x = 1$. The black dotted line shows the Keplerian rotation profile. $R_{tr}$ marks the transition from the rigidly rotating star to the accretion disk, while the exact boundary is not defined well (Paczýnski 1991; Popham & Narayan 1991).

# Lee & Yoon (3)




[ 降着率: 4 x $10^{-3}$ $M_\odot$/yrの場合 ]

Γ=0.2に達した時点でciriticalになり、降着率が低下すると仮定

(いろんな値で計算)