Evolution of Low and Intermediate Mass Stars

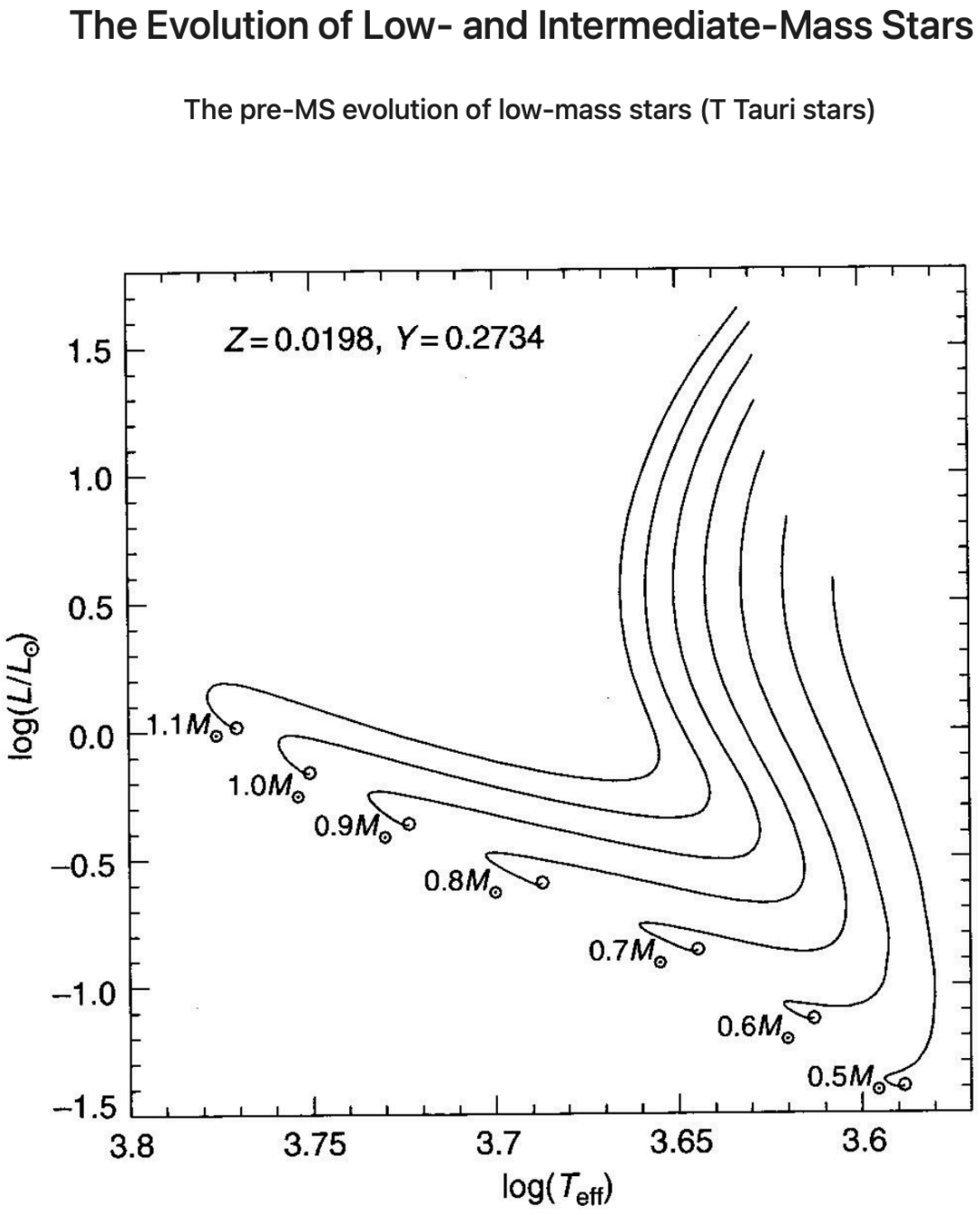
1. Introduction

- Distinction between low-mass stars ($M < 2M_\odot$) and intermediate-mass stars ($2M_\odot < M < 8M_\odot$)
- Common features and differences in their evolution

2. Classification and Initial Stages

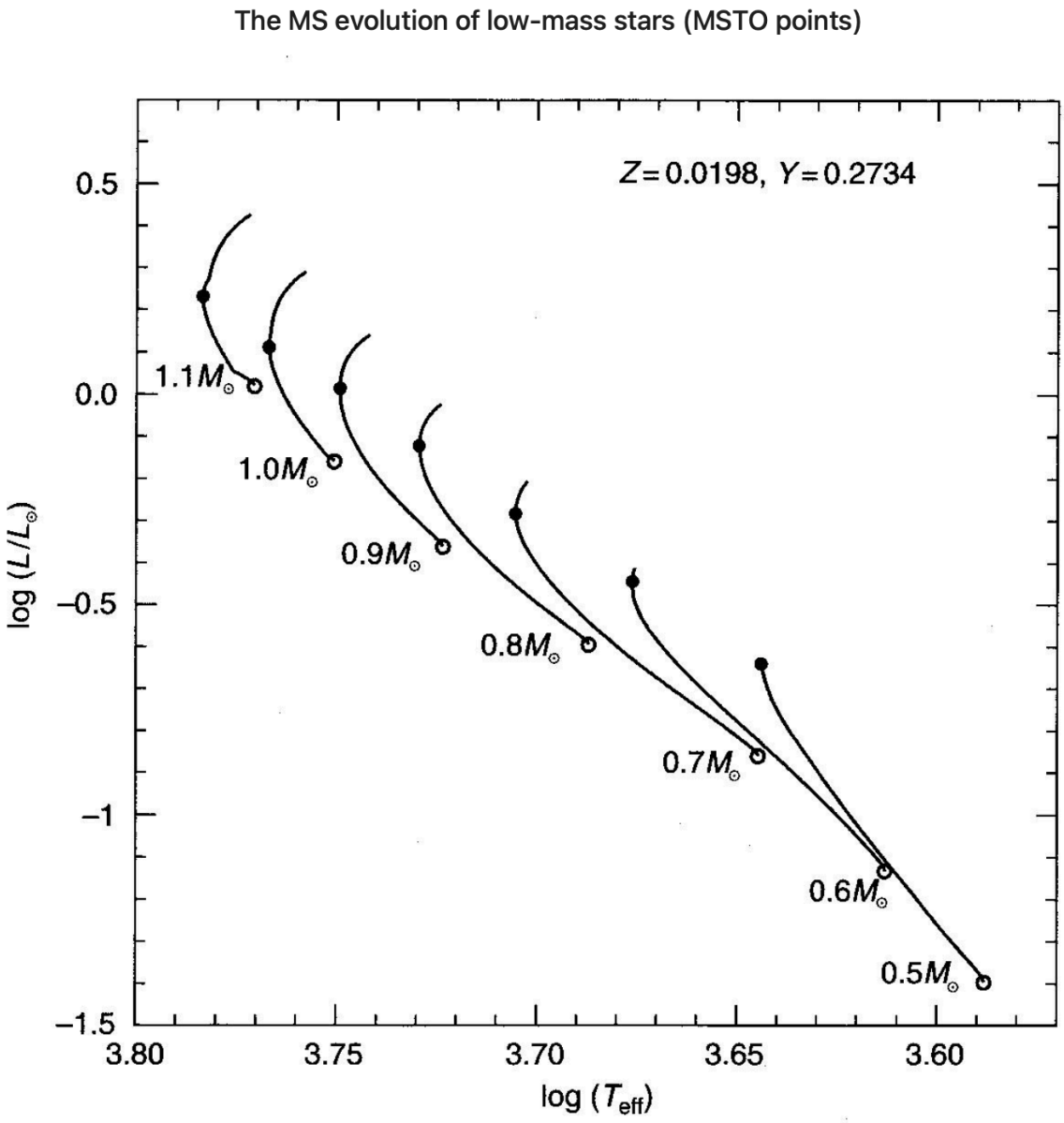
- Initial mass of $1.2M_\odot$ divides stars based on dominant hydrogen burning process:
  - Below $1.2M_\odot$: pp chains
  - Above $1.2M_\odot$: CNO cycle
- Pre-Main Sequence (pre-MS) evolution

[Fig 1: The pre-MS evolution of low-mass stars]



3. Main Sequence (MS) Evolution

[Fig 2: The MS evolution of low-mass stars]



- Zero Age Main Sequence (ZAMS)
- Main Sequence Turn-Off (MSTO)

4. Post-Main Sequence Evolution

4.1 Red Giant Branch (RGB)

- Subgiant phase
- Lower RGB
- Upper RGB
- He-core flash at the RGB tip (for low-mass stars only)

[Fig 3: The MS and RGB evolution of low- and intermediate-mass stars up to the RGB tip]

The MS and RGB evolution of low- and intermediate-mass stars (the RGB tip)

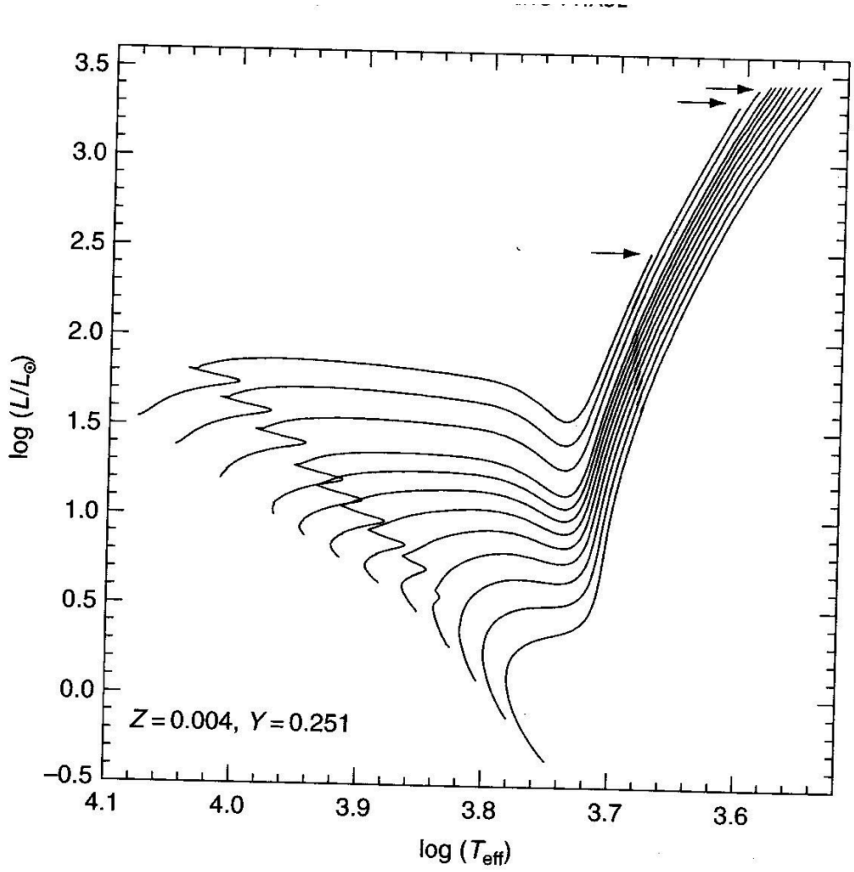


Figure 5.13 The HRD for both the core and shell H-burning phases of low-mass stars for the labelled chemical composition. The RG phase begins when the stars start to evolve at almost constant $T_{\rm eff}$ and increasing luminosity. The various evolutionary tracks correspond to the following stellar masses: $M/M_{\odot}$ =0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.8, 2.0, 2.2. The arrows mark the location of the tip of the RGB for the $2.2M_{\odot}$ and $2M_{\odot}$ models, and for those less massive (that has an approximately constant luminosity)

4.2 Horizontal Branch (HB)

- A stage of stellar evolution following the Red Giant Branch, where stars burn helium in their cores

4.3 Asymptotic Giant Branch (AGB)

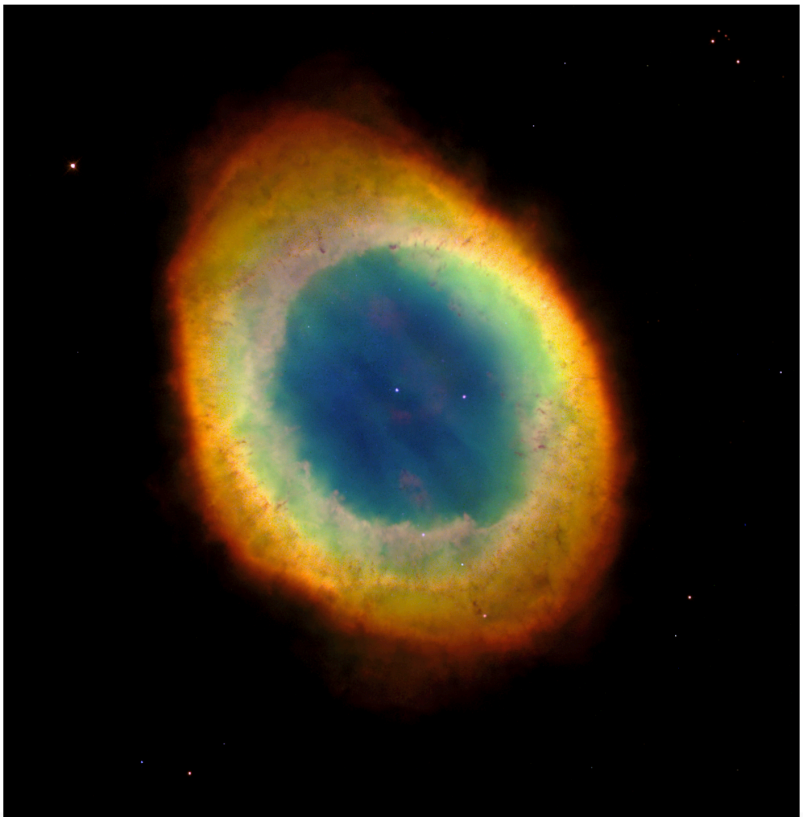
- S-process in low-mass AGB stars
- Hot-bottom burning in massive AGB stars
- C ignition and formation of ONe WDs in super-AGB stars

4.4 Final Stages

- Superwind phase
- Formation of planetary nebula

[Fig 6: An image of a planetary nebula]

The planetary nebula M57 in the constellation Lyra. This is the envelope of an asymptotic giant branch star that was recently (~1600 years ago) expelled by it in a super-wind event. The white dwarf remnant is at the center of the nebula.



- White Dwarf (WD) formation:
    - CO WD for most low and intermediate-mass stars

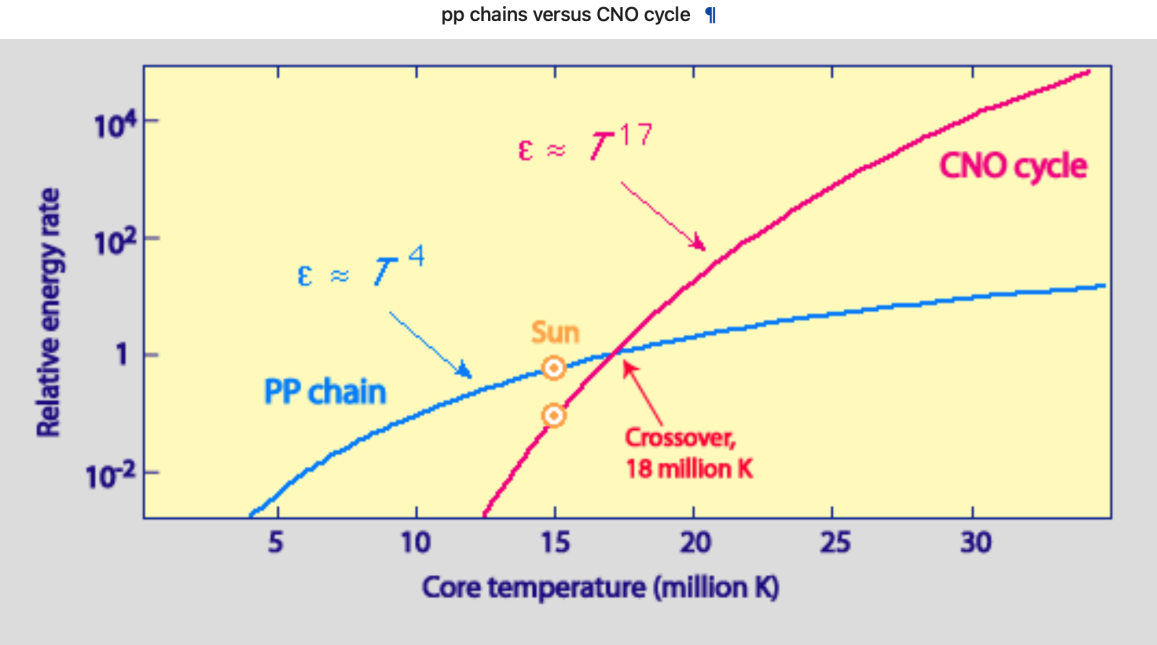
- ONe WD for super-AGB stars (upper mass limit)

5. Binary System Evolution

- Focus on novae in close binary systems

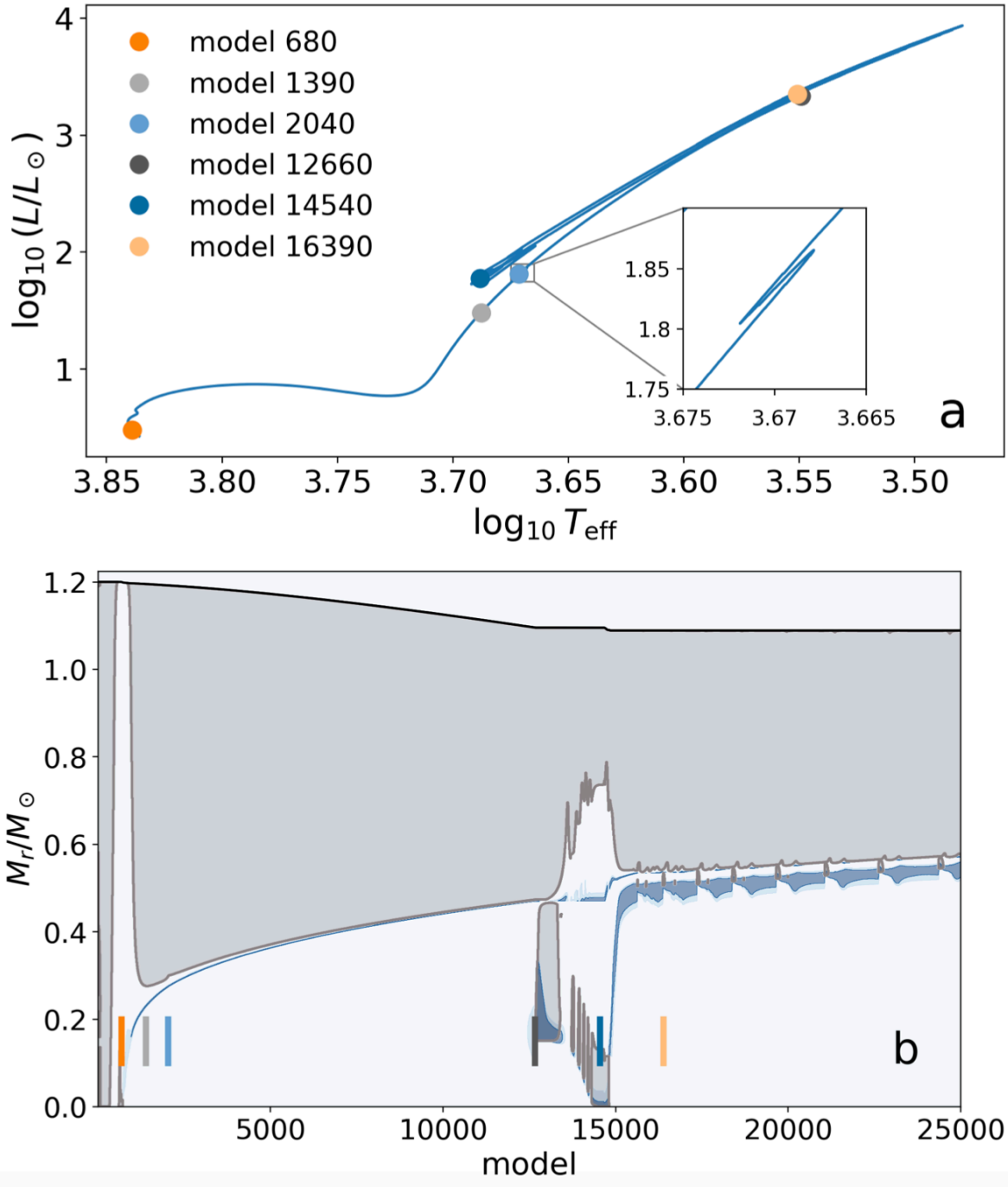
6. Energy Generation

[Fig 5: The relative energy generation rate as a function of stellar core temperature for pp chain and CNO cycle H burning]



7. Evolutionary Timeline

[Fig 4: Top panel: the HRD of a low-mass star with evolutionary points marked at different location; Lower panel: a Kippenhahn diagram with the same locations indicated on the time axis]



8. Unsolved Problems in Low-Mass Star Evolution

8.1 Extra Mixing on Upper RGB

- Occurs above the bump luminosity
- Explanation of bump luminosity:
  - H-burning shell crossing
  - Erasing of chemical composition jump left by convective envelope at end of 1st dredge-up

8.2 Extra Mixing on AGB

- Needed to ingest protons in C-rich radiative layers
- Activates s-process
- Main neutron source reaction: 13C(α,n)16O

8.3 Thermohaline Convection

- Possible mechanism for RGB extra mixing

9. Problem Set

1. Estimate the mean molecular weight depletion produced by the reaction 3He(3He,2p)4He
2. Estimate the C isotopic ratio reached at 25 MK