MARTIN SCHWARZSCHILD (1958)

If simple perfect laws uniquely rule the Universe, should not pure thought be capable of uncovering this perfect set of laws without having to lean on the crutches of tediously assembled observations? True, the laws to be discovered may be perfect, but the human brain is not. Left on its own, it is prone to stray, as many past examples sadly prove. In fact, we have missed few chances to err until new data freshly gleaned from nature set us right again for the next steps. Thus pillars rather than crutches are the observations on which we base our theories; and for the theory of stellar evolution these pillars must be there before we can get far on the right track.
WHAT IS A STAR?

- Is bound by self-gravity
- Radiates energy supplied by an internal source

It follows that stars must evolve

NOT A STAR:

- Wandering stars (planets)
- Guest stars (comets)
From the definition, two scenarios are possible:

- Violation of first condition (no longer bound by self gravity)
- Violation of second condition (no more internal energy)
OBSERVATIONS

Information we can gather is quite restricted!

- Apparent brightness
- Related to the intrinsic luminosity
  \[ I_{\text{obs}} = \frac{L}{4\pi d^2} \]
- Hard to measure distance \( d \)
- Parallax
From the spectral lines we can obtain

- Chemical composition
- Helium first suggested by spectral lines in the Sun (1860)
BLACK BODY SPECTRUM
OBSERVATIONS

- How to measure temperature?
- Take full spectrum or at least two fluxes

\[ B - V = -2.5 \log_{10} \left( \frac{F_B}{F_V} \right) \]

- This gives a fair measure for stellar temperatures
- Can range from \(~1000\)K to \(~100\ 000\)K
- Sun 5780K
- Can estimate total luminosity

\[ L = 4\pi R^2 \sigma T_{\text{eff}}^4 \]
Assumptions

For the theory of stellar structure and evolution

- Isolation
- Uniform initial composition
- Spherical symmetry
Look for correlation in the two fundamental observable quantities:
Can explain scatter in two ways:

- Different age
- Different mass

We only see a snapshot of stars with different masses and ages. How to solve this dilemma?
HERTZSPRUNG-RUSSELL DIAGRAM

Find a population with the same age!
Conclusions one can draw

- Location on main sequence is determined by initial mass
- Being on or off main sequence determined by age

However:

- Still unable to determine evolutionary track unless we know cluster ages
- Observations alone are unable to answer this
- Need theoretical models
TEST OF FIRST CONCLUSION

(Location on main sequence is determined by initial mass)

- Measure mass-radius relation for main sequence stars
TIMESCALES FOR STELLAR EVOLUTION

- Dynamical timescale
  \[ \tau_{\text{dyn}} \approx \frac{1}{G\bar{\rho}} \approx 1000 \sqrt{\left(\frac{R}{R_\odot}\right) \left(\frac{M_\odot}{M}\right)} \text{ s} \]

- Thermal timescale
  \[ \tau_{\text{th}} \approx \frac{GM^2}{RL} \approx 10^{15} \left(\frac{M}{M_\odot}\right)^2 \left(\frac{R_\odot}{R}\right) \left(\frac{L_\odot}{L}\right) \text{ s} \]

- Nuclear timescale
  \[ \tau_{\text{nuc}} \approx \frac{\epsilon MC^2}{L} \approx 4.5 \times 10^{20} \left(\frac{M}{M_\odot}\right) \left(\frac{L_\odot}{L}\right) \text{ s} \]
NUCLEAR REACTIONS
THE P–P CHAIN

- Most abundant element in stars is H
- Fusion to He releases energy, but would require an encounter of 3 or 4 particles, statistically unlikely
- Thus we have a chain of events
NUCLEAR REACTIONS
THE CNO BI-CYCLE

- Happens at a later stage
- Uses carbon, nitrogen, and oxygen as catalysts
## MAJOR NUCLEAR BURNING PROCESSES

<table>
<thead>
<tr>
<th>Nuclear Fuel</th>
<th>Process</th>
<th>$T_{\text{threshold}} \times 10^6\text{K}$</th>
<th>Products</th>
<th>Energy per nucleon (Mev)</th>
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</thead>
<tbody>
<tr>
<td>H</td>
<td>PP</td>
<td>~4</td>
<td>He</td>
<td>6.55</td>
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<tr>
<td>H</td>
<td>CNO</td>
<td>15</td>
<td>He</td>
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<td>C,O</td>
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<tr>
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<td>C+C</td>
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<td>O,Ne,Na,Mg</td>
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<tr>
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<td>Ne+Ne</td>
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<td>O,Mg</td>
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<td>Si</td>
<td>Alpha</td>
<td>3000</td>
<td>Co,Fe,Ni</td>
<td>&lt;0.18</td>
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</tbody>
</table>
S AND R PROCESSES
SOURCES OF ELEMENTS

- Big Bang fusion
- Dying low-mass stars
- Exploding massive stars
- Cosmic ray fission
- Merging neutron stars
- Exploding white dwarfs
EVOLUTION AND THE HR DIAGRAM