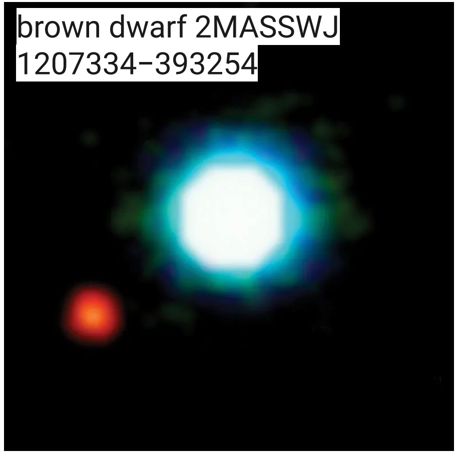
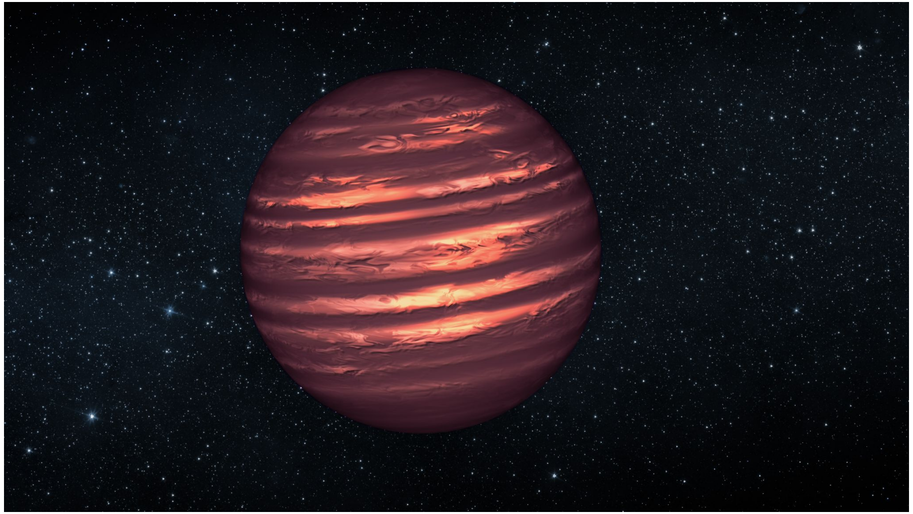


Brown Dwarfs:

The Failed Stars

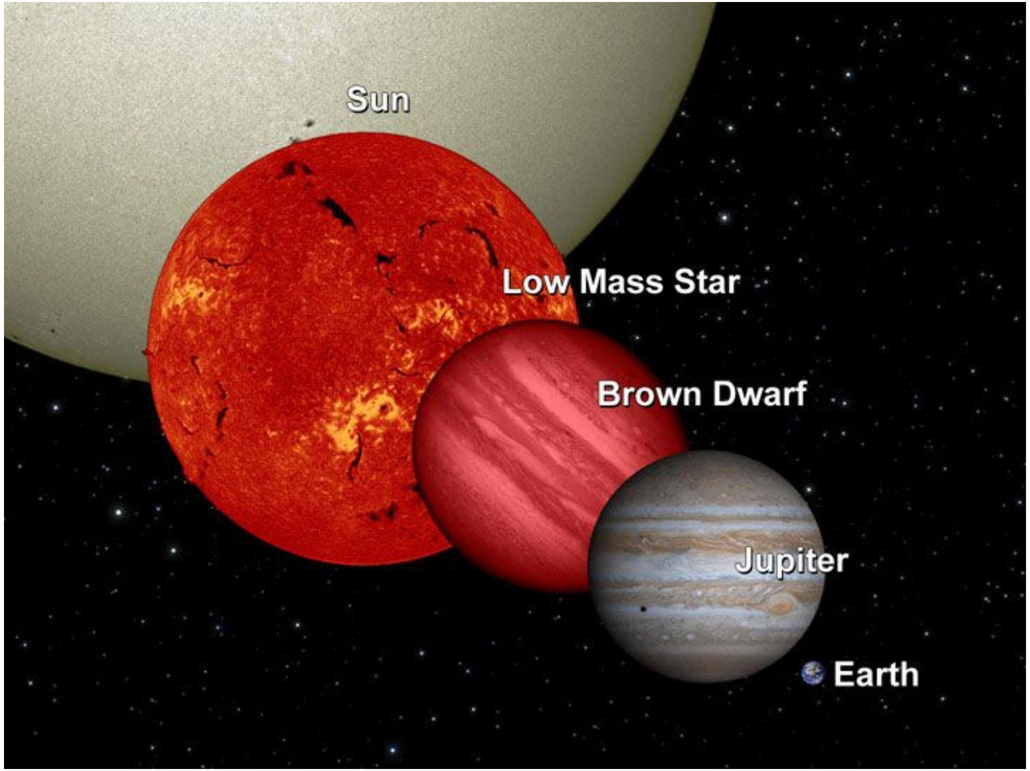
Frank Genty, Anthony Pizzareli, Khovesh Ramdin



Points of Discussion

- Intro
- Temperature/Luminosity intro discussion (span in HR Diagram)
- Typical density, pressure, composition
- Equation of State discussion, quantum effects
- Application of Saha equation
- Energy Transport/ Temperature Gradient
- Atmosphere
- Nuclear fusion discussion (special cases+limitations)
- Conclusion :Discussion of lifespan

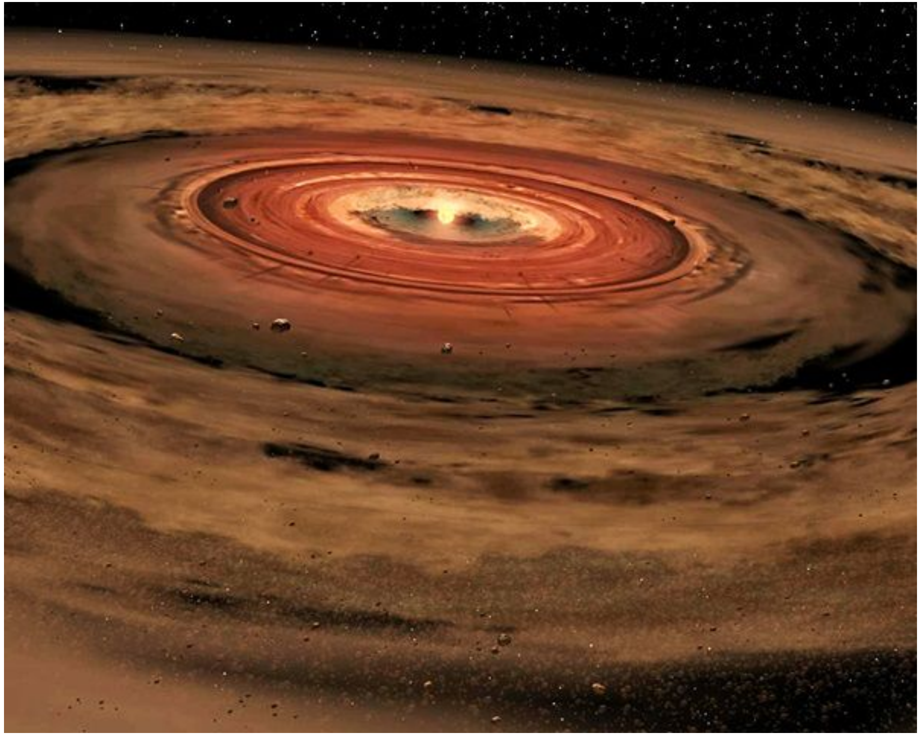
Typical Structure



https://earthsky.org/space/definition-what-are-brown-dwarfs/

- Usually defined as between 13 and 80 Jupiter masses
- Not enough mass to sustain Hydrogen fusion
- Can fuse deuterium
- More massive brown dwarfs can fuse lithium ($65M_J$)
- Roughly 1 Jupiter Radius

Formation Process

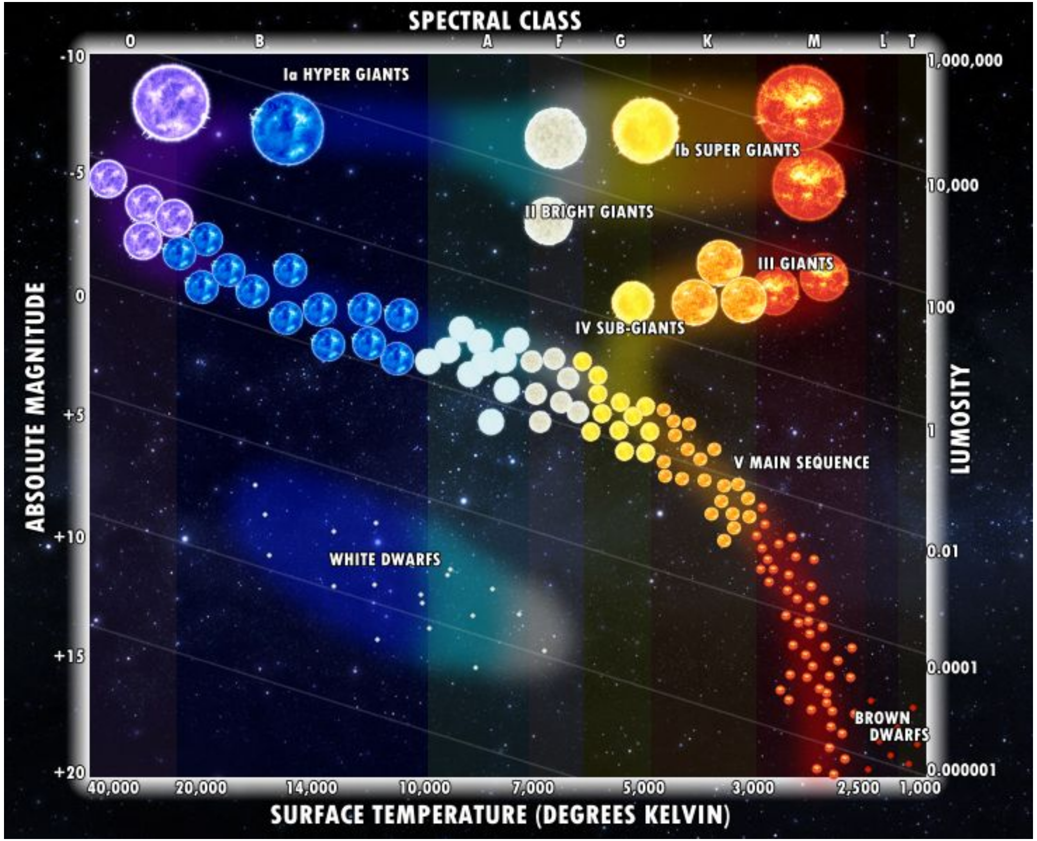


https://astronomy.com

- Brown dwarfs start formation like a star, in a gaseous cloud
- In a normal star, deuterium fusion is a temporary step to formation
- Brown dwarfs do not collect more mass and are stuck at the deuterium fusion stage
- Sometimes they can form as a binary companion to regular stars

HR Diagram

- Compared to our sun, which has a surface temperature of 5778K
- Typically observed between 700K and 2400K
- Usually around 1/100,000 solar luminosity
- Not very luminous or hot…



http://sttff.antspad.net/ast/hrd.html

Typical Composition

- High mass allows for a lot of Hydrogen and Helium
- Traces of lithium remain in the object
    - Lithium normally gets destroyed by fusion
- Older brown dwarfs contain a metallic Hydrogen core
- Atmosphere contains amounts of methane and water vapor (infrared spectrum)

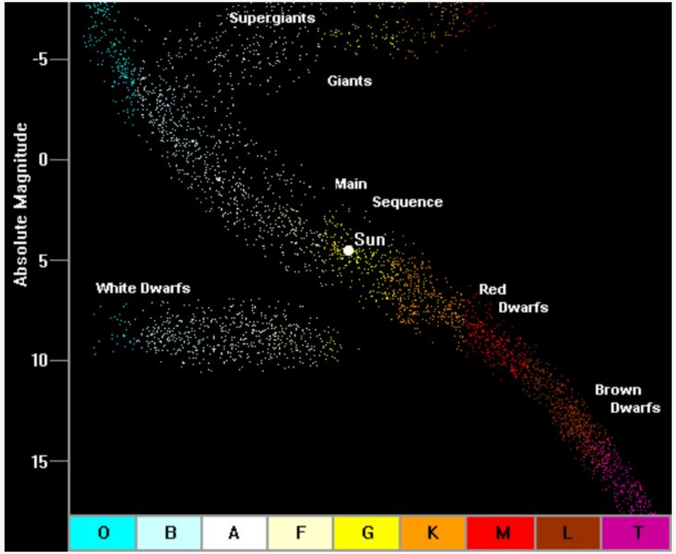


Image credit: Steven Dutch of UW Green Bay.

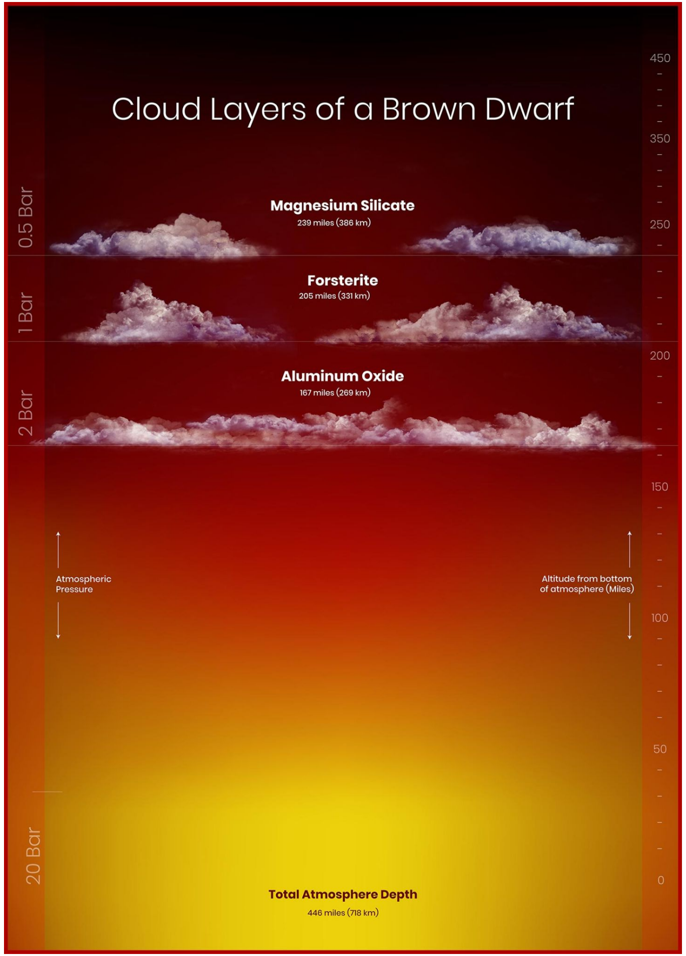
Classes of Brown Dwarfs

[Type L, T & Y Cool Brown Dwarf Stars]

- Class Y (Ultra-Cool) Brown Dwarfs have a temperature lower than 600K
  - One extremely cool Brown Dwarf was found with a surface temperature of 300K (30ºC or 86ºF)
  - No methane content
- Class T (Methane) Brown Dwarfs, surface between 700K and 1300K
  - More likely dark magenta
  - Spectra dominated by methane absorption lines
  - broad absorption features from the alkali metals Na and K
  - Lack the FeH and CrH bands that "L" type dwarfs exhibit
- Class L (Dwarf Stars) Temperatures between 1300K and 2000K
  - Can include brown dwarfs and really cool stars
  - emission bands (FeH, CrH, MgH, CaH)
  - alkali metal lines (Na I, K I, Cs I, Rb I)

Atmosphere

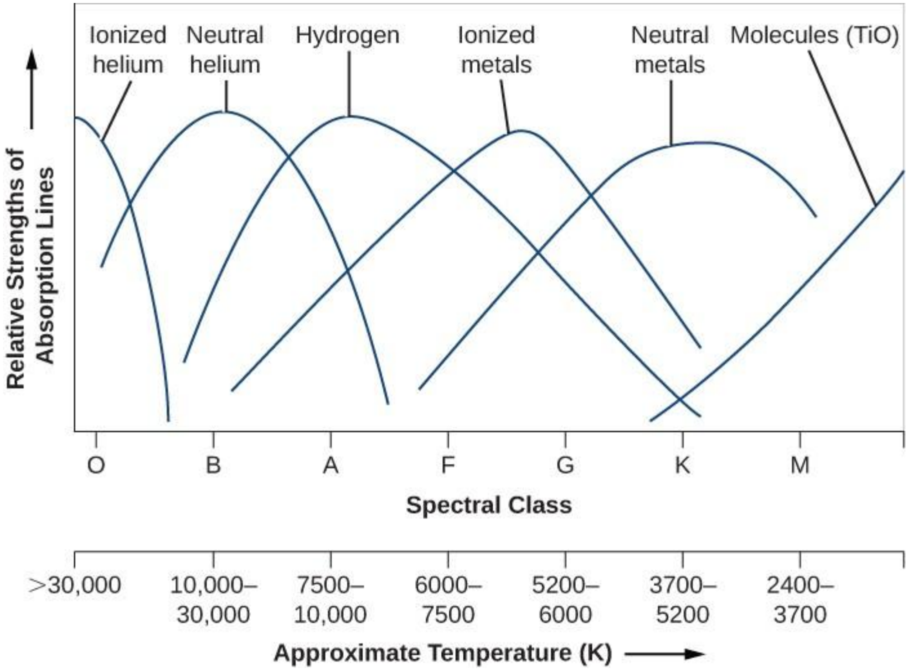
- Class Y dwarfs in their cool state have more complex atmospheres
  - Cool enough to allow water ice and eventually ammonia ice clouds
- Class T Dwarfs have a very thin atmosphere, layers sink as the object cools
- The hottest dwarfs can have different layers with clouds of different compositions
  - Potassium Iodide in the upper atmosphere (MgSiO3 too)
  - Forsterite (Mg_2SiO_4) as the pressure increases
  - Lowest layer is aluminum oxide



https://scitechdaily.com/astronomers-probe-layer-cake-structure-of-monster-brown-dwarfs-alien-atmosphere/

Spectral Classes for Stars

Spectral Class	Color	Approximate Temperature (K)	Principal Features	Examples
O	Blue	> 30,000	Neutral and ionized helium lines, weak hydrogen lines	10 Lacertae
B	Blue-white	10,000–30,000	Neutral helium lines, strong hydrogen lines	Rigel, Spica
A	White	7500–10,000	Strongest hydrogen lines, weak ionized calcium lines, weak ionized metal (e.g., iron, magnesium) lines	**Sirius, Vega**
F	Yellow-white	6000–7500	Strong hydrogen lines, strong ionized calcium lines, weak sodium lines, many ionized metal lines	Canopus, Procyon
G	Yellow	5200–6000	Weaker hydrogen lines, strong ionized calcium lines, strong sodium lines, many lines of ionized and neutral metals	**Sun**, Capella
K	Orange	3700–5200	Very weak hydrogen lines, strong ionized calcium lines, strong sodium lines, many lines of neutral metals	Arcturus, Aldebaran
M	Red	2400–3700	Strong lines of neutral metals and molecular bands of titanium oxide dominate	**Betelgeuse**, Antares
L	Red	1300–2400	Metal hydride lines, alkali metal lines (e.g., sodium, potassium, rubidium)	Teide 1
T	Magenta	700–1300	Methane lines	Gliese 229B
Y	Infrared[1]	< 700	Ammonia lines	WISE 1828+2650

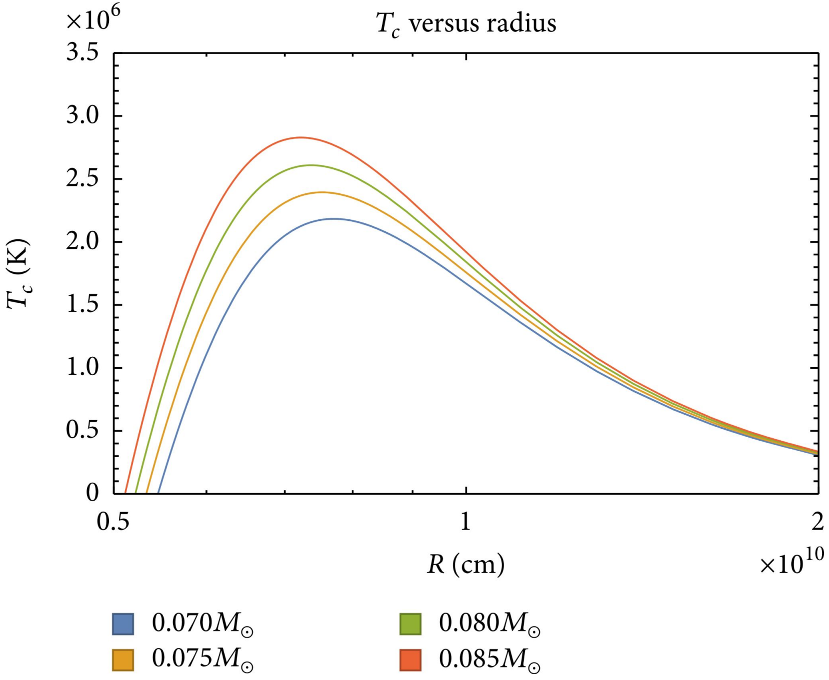


https://uwm.pressbooks.pub/astronomy/chapter/chapter-17-section-17-3-the-spectra-of-stars-and-brown-dwarfs/#browndwarfs

Equation of State/ Quantum Effects

- Sayantan Auddy, Shantanu Basu, S. R. Valluri

$P = K\rho^{(1+1/n)}$, Polytropic equation $K = C\mu_e^{-5/3}(1+\gamma+\alpha\psi)$, n = 3/2



$$\rho_c = 1.28412 \times 10^5 \left(\frac{M}{M_\odot}\right)^2 \frac{\mu_e^5}{(1+\gamma+\alpha\psi)^3}\ \text{g/cm}^3,$$

$$P_c = 3.26763 \times 10^9 \left(\frac{M}{M_\odot}\right)^{10/3} \frac{\mu_e^{20/3}}{(1+\gamma+\alpha\psi)^4}\ \text{Mbar.}$$

$$T_c = 7.68097 \times 10^8\ \text{K} \left(\frac{M}{M_\odot}\right)^{4/3} \frac{\psi\mu_e^{8/3}}{(1+\gamma+\alpha\psi)^2}.$$

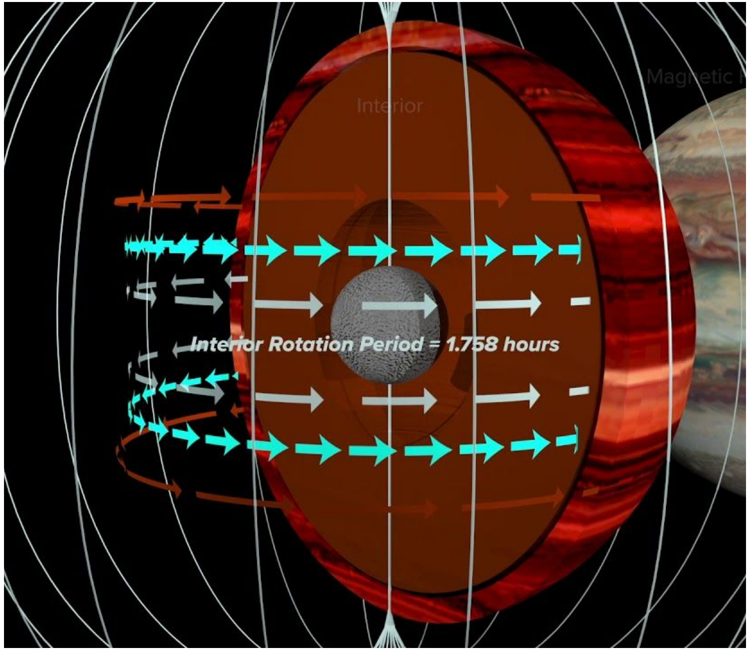
$$R = 2.80858 \times 10^9 \left(\frac{M_\odot}{M}\right)^{1/3} \mu_e^{-5/3}(1+\gamma+\alpha\psi)\ \text{cm.}$$

$$\psi = \frac{k_B T}{\mu_F} = \frac{2m_e k_B T}{(3\pi^2\hbar^3)^{2/3}}\left[\frac{\mu_e}{\rho N_A}\right]^{2/3}, \quad \alpha = 5\mu_e/2\mu_1$$

$$\gamma = (\partial \log T/\partial \log \rho)_s$$

Density, Pressure

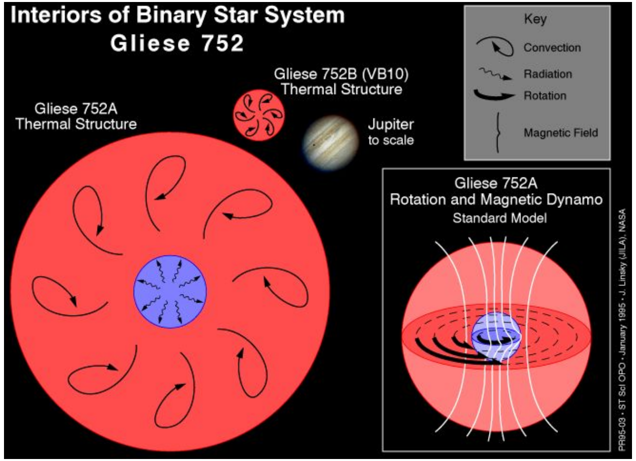
- Early in life, a brown dwarf is supported by deuterium burning if present
- After there is no more deuterium, the core compresses leading to partial electron degeneracy pressure
- Because of the pressure and ionization, the core forms metallic hydrogen



https://www.amnh.org/explore/news-blogs/research-posts/brown-dwarf-wind-speed

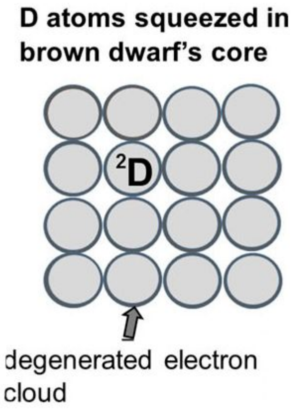
Energy Transport

- Schwarzschild Criterion for convection met
- Fully convective ~ mixes all material from formation for Lithium, deuterium burning

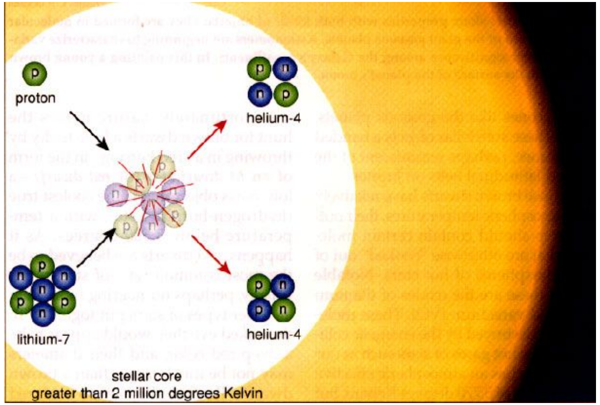


$$\boxed{\left|dT/dr\right|_{\mathrm{ad}} < \left|dT/dr\right|_{\mathrm{rad}}}$$

Nuclear Fusion



- Core temp too low to support stable fusion
- Lithium fusion occurs at T ~ 2.5*10^6 K
- Deuterium fusion occurs at T~ 10^6 K
- Convection ensures all material is available for fusion for duration in which star maintains necessary temperature
- M ~ 60 MJ sized dwarfs have a chance for fusion for 10^6 years after which it becomes too cool

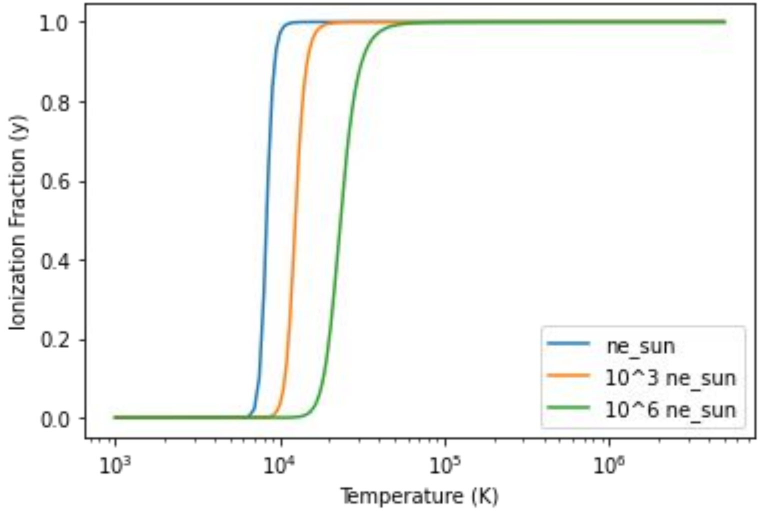


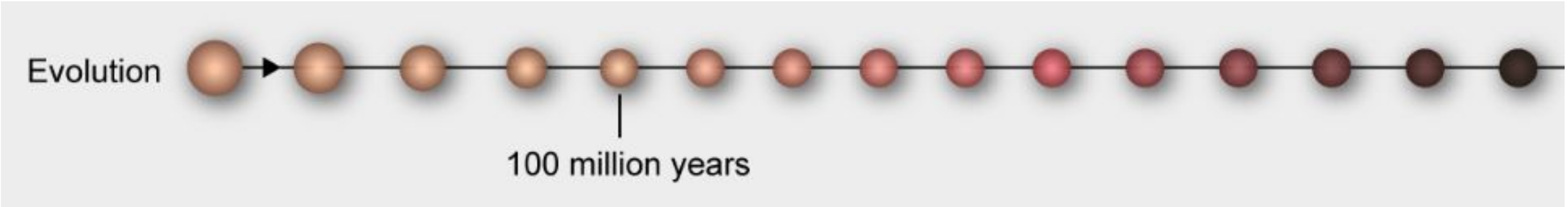
$$^2_1\mathrm{D} + ^2_1\mathrm{D} + 2\pi^\circ = ^4_2\mathrm{He}.$$

Saha Equation/ Cooling

$$\frac{n_{II}}{n_I} = \frac{2Z_{II}}{n_e Z_I}\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2} e^{-\chi_I/kT}$$

- Hydrogen composition dominant and initial state generally has variation in densities
- Progressively cools and temperature becomes too low for ionization

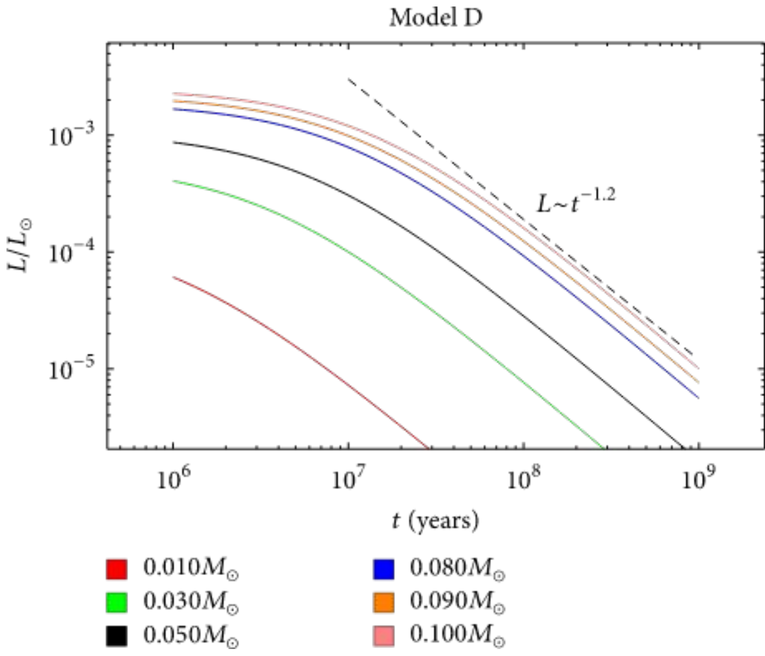




Cooling

- Rate of cooling can be approximated numerically for polytropes with n =1.5
- Fusion of deuterium and lithium can sustain luminosity for higher mass brown dwarfs for longer periods
- Low mass brown dwarfs are not able to sustain extended periods of any fusion

$$L \simeq L_{\odot} \left(\frac{M}{M_{\odot}} \right)^{2.63} \left(\frac{t}{10^7 \text{ yr}} \right)^{-1.2}$$



Lifespan

- Some may briefly fuse lithium or deuterium until temperature becomes too low
- Don’t really die, just cools off and approaches 0 luminosity
- Slowly cool for billions of years, eventually becomes a cold ball of gas
- As it cools, luminosity lowers, making it cool even slower

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