Stellar Evolution

Interstellar extinction

Fig. 2 View of the Milky Way over Cathedral Rock, seen from the Cathedral Rock Trailhead on Back O' Beyond Road, Sedona, Arizona. The dark parts of the milky way are there because dust is occluding the light, not because there are no stars there.

We can modify the distance modulus to account for **interstellar extinction**. This accounts for all the light that is emitted from stars but is either scattered or absorbed before it reaches us.

$$m_\lambda = M_\lambda + 5\log_{10}(d) - 5 + A_\lambda \quad (1)$$

A_λ is the number of magnitudes of interstellar extinction present.

In between the stars

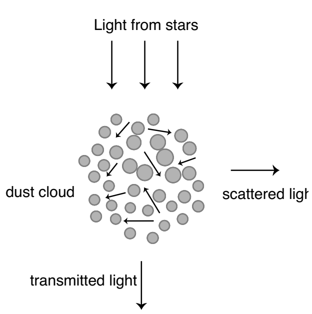

Fig. 3 Light from stars passes into a dust cloud. Inside the cloud the light interacts with particles. Some light gets transmitted, some reflected.

The fractional change in the intensity of the light after passing through a dust cloud is:

$$\frac{I_\lambda}{I_{\lambda,0}} = e^{-\tau_\lambda} \quad (2)$$

where $I_{\lambda,0}$m is the intensity of the light if there was no interstellar extinction.τ_λ is the **optical depth.** Recalling the change in apparent magnitude:

$$m_1 - m_2 = -2.5\log_{10}\left(e^{-\tau_\lambda}\right) = 2.5\tau_\lambda \log_{10} e = 1.086\tau_\lambda \quad (3)$$

Thus we can say the change in magnitude is essentially equal to the optical depth along the line of sight.

The optical depth τ_λ will be given by:

$$\tau_\lambda = \sigma_\lambda \int_0^s n_d(s')ds = \sigma_\lambda N_d \quad (4)$$

Mie Scattering

When the particles are the same order of magnitude as the light, **Mie Scattering** can be used to understand the effects.

$$\sigma_\lambda \propto \frac{a^3}{\lambda} \quad (5)$$

(a is the radius of the dust particles.)

What is the stuff?

Fig. 4 Some polycyclic aromatic hydrocarbons: $C_{14}H_{10}$ (anthracene), $C_{24}H_{12}$ (coroene), and $C_{42}H_{18}$ (hexabenzocoronene)

Gasses

Most (~70 %) of the ISM is hydrogen in various forms: neutral H I, ionized H II, and molecular H_2. Helium makes up most of the rest.

21-cm line

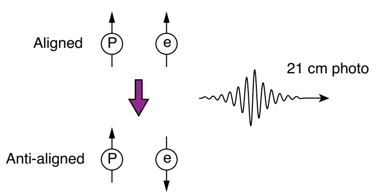

Fig. 5 When the electron spin flips and becomes anti-aligned with the proton, a photon is released. The energy is small, 5.9×10^{-6} eV, which correlates to wavelength of about 21 cm.

For more see Feynman Lectures III - 12

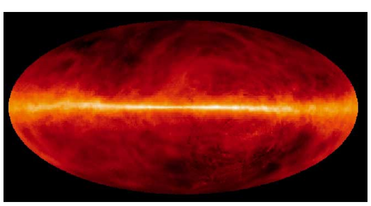

Fig. 6 View of the milky way galaxy taken at 1420 MHz (i.e. 21 cm) Neutral Hydrogen exists in the gas clouds shown in this false color image.

Credit: J. Dickey (UMn), F. Lockman (NRAO), SkyView

Protostars

When will gravitational collapse occur? There are two main sources of energy: gravitational and kinetic. Gravitational will lead to contractions, kinetic creates expansion through gas pressure.

Take a cloud with mass M_c and radius R_c. The gravitational potential energy is approximately:

$$U \sim -\frac{3}{5}\frac{GM_c^2}{R_c} \quad (6)$$

The kinetic energy of N particles will be approximately:

$$K = \frac{3}{2}NkT \quad (7)$$

Recasting this in terms of the mean molecular weight, μ,

$$N = \frac{M_c}{\mu m_H}$$

If the kinetic energy is than half the gravitational energy, then collapse will be possible.

$$\frac{3M_c kT}{\mu m_H} < \frac{3}{5}\frac{GM_c^2}{R_c} \quad (8)$$

The radius of the cloud R_c can be expressed in terms of the initial mass density:

$$R_c = \left(\frac{3M_c}{4\pi\rho_0}\right)^{1/3}$$

Which when substituted back into (8), we get:

$$M_J \simeq \left(\frac{5kT}{G\mu m_H}\right)^{3/2}\left(\frac{3}{4\pi\rho_0}\right)^{1/2} \quad (9)$$

This is the **Jeans mass**. Or, in terms of a **Jeans length**,

$$R_J \simeq \left(\frac{15kT}{4\pi G\mu m_H\rho_0}\right)^{1/2} \quad (10)$$

A more thorough treatment would have to include the pressure from the surrounding ISM. The **Bonner-Ebert mass** captures the physics of this added complexity:

$$M_{\mathrm{BE}} = \frac{c_{\mathrm{BE}}v_T^4}{P_0^{1/2}G^{3/2}} \quad (11)$$

where $v_T \equiv \sqrt{\frac{kT}{\mu m_H}}$ is the isothermal speed of sound. c_{BE} is a dimensionless constant approximately equal to 1.18.

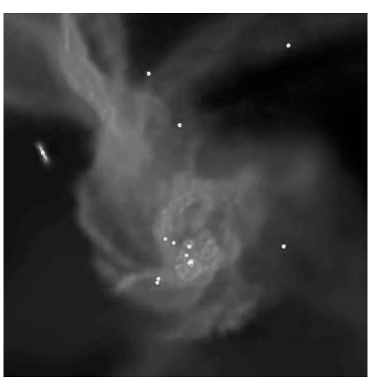

Fig. 8 Star formation simulation

Free fall collapse

The basic equation of motion for a gravitational system:

$$\frac{d^2r}{dt^2} = -G\frac{M_r}{r^2} \quad (12)$$

Some differential equations leads to:

$$t_{\rm ff} = \left(\frac{3\pi}{32}\frac{1}{G\rho_0}\right)^{3/2} \quad (13)$$

Speed of sound

$$t_{\rm pressure} = \frac{r_0}{c_s} \quad (14)$$

and the speed of sound is:

$$c_s = \left(\frac{\gamma kT}{\mu m_p}\right)^{1/2} \quad (15)$$

Compare these two times

$$t_{\rm ff} < t_{\rm pressure}$$

$$\left(\frac{3\pi}{32G\rho_0}\right)^{1/2} < r_0\left(\frac{\mu m_p}{\gamma kT}\right)^{1/2} \quad (16)$$

Jeans Length

$$r_J = \left(\frac{3\pi\gamma kT}{32G\rho_0\mu m_p}\right)^{1/2} \quad (17)$$

Star Formation

Perturbation

A shockwave from a nearby supernova can trigger the gravitational collapse. The molecular cloud collapses.

Collapse

However, it cannot collapse for ever, since the angular momentum will be conserved, and as it gets smaller, its rotates faster.

$$\frac{GM}{r_f^2} = \frac{v_f^2}{r_f} \quad (18)$$

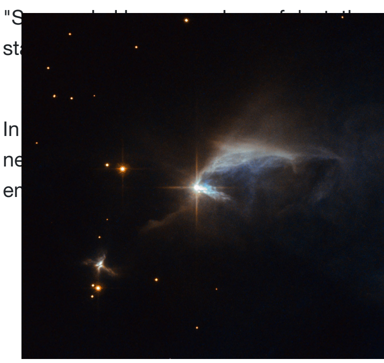

Fig. 9 A pre-main-sequence star: HBC 1

"S ... ubject of this NASA/ESA Hubble Space Telescope image is a young pre-main-sequence st ... nature and adolescent phase of life, hence its classification — most of a Sun-like star's life is spent in a stage comparable to human adulthood dubbed the main sequence.

In ... ection nebula known as IRAS 00044+6521. Formed from clouds of interstellar dust, reflection ne ... ir own and instead — like fog encompassing a lamppost — shine via the light from the stars en ... nnot ionise the nebula's non-gaseous contents, as with brighter emission nebulae, scattered starlight can make the dust visible.

What makes this seemingly ordinary reflection nebula more interesting are three nearby Herbig–Haro objects known as HH 943, HH 943B and HH 943A — which are not visible in this image — located within IRAS 00044+6521 itself. Herbig–Haro objects are small patches of dust, hydrogen, helium and other gases that form when narrow jets of gas ejected by young stars such as HBC 1 collide with clouds of gas and dust. Lasting just a

ESA/Hubble

few thousand years, these objects rapidly move away from their parent star before dissipating into space.""

Hot gas moves out

Nuclear Fusion Begins

As the gas gets denser, it also gets hotter. Eventually fusion will commence.

A star (like our sun) is born

This covers stars with masses ranging from $0.5M_\odot$ to $5M_\odot$. Stars in the classes: A, F, G, K fit this description.

Main sequence life

For our sun, the Hydrogen supply will last about 10.6 billion years. Fusion of Hydrogen to Helium occurs in the core. Over this time, the Luminosity will increase. (from $.7L_\odot$ to $2.2L_\odot$)

Leaving the Main sequence

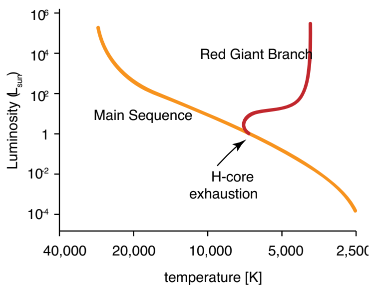

Fig. 10

Once the hydrogen in the core is depleted, the star will enter the red giant phase. During this phase, the star will get bigger, a lot bigger.

After the hydrogen is depleted, the core is mostly helium. The pp chain will stop. The core will still be hot, and this heat will power H fusion in a shell surrounding the predominantly He core.

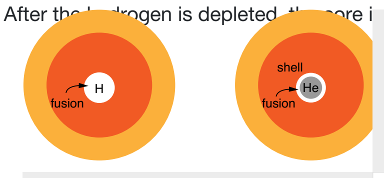

Fig. 11 Leaving the main sequence

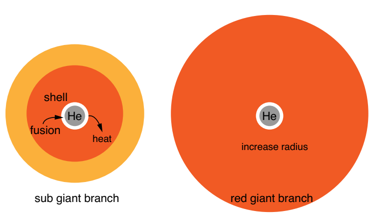

Fig. 12 Sub giant to Red Giant

The heat from the CNO reaction in the shell will cause the out regions (hydrogen envelope) to get larger. It may increase from $1.6R_\odot$ to $170R_\odot$

Red Giants

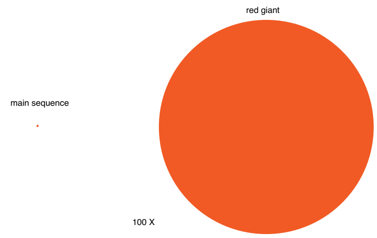

Fig. 13

He Flash

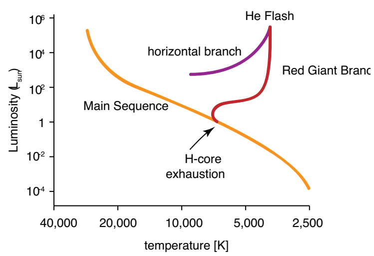

Fig. 14

Helium created by the H fusion processes goes to the core and the core increases. The gravitational attraction in the core would lead to a collapse, but there is electron degeneracy pressure preventing that. **Degeneracy** means the electrons are close enough to bring the Pauli exclusion principle into play. (This says that two electrons cannot share the same state: i.e. position.)

Asymptotic Branch

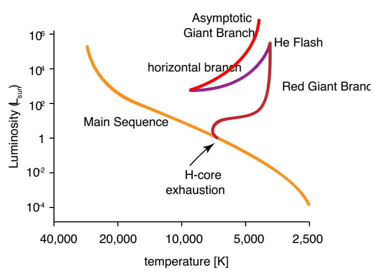

Fig. 15 Now, another shell of forms around the core. He will begin to fuse into carbon.

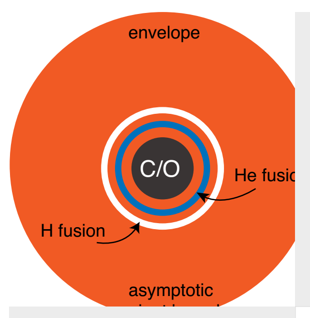

Fig. 16 An asymptotic Red giant

Planetary Nebula

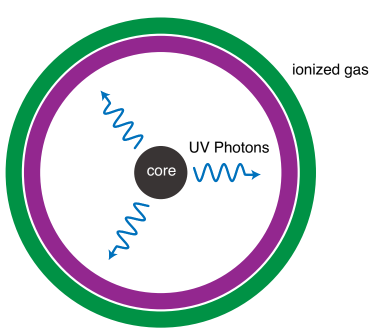

Fig. 17

The shells of the AGB star eventually get pushed out by the inner core's instability. An enormous stellar wind forms and pushes everything out. The inner core is still hot, and emits UV radiation that causes these gasses to fluoresce.

White Dwarf

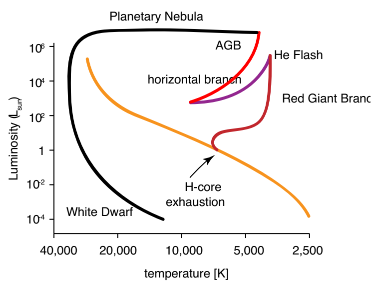

Fig. 19 The white dwarf on the HR Diagram

The final form of a sun like star is a white dwarf. Our sun will eventually loose about 40% of its mass, and will spend the next trillion years just cooling down - no more fusion.

What	Time	Activity
Protostar	50 Myr	Gravitational Attraction
Main Sequence	10 Gyr	Fusion of H to He in the core
Red Giant Branch	1 Gyr	Fusion of H to He in shell
Horizontal Branch	100 Myr	Fusion of H to He in shell, He to C in core
Asymptotic Giant Branch	20 Myr	Fusion of H to He in outer shell, He to C in inner shell
Planetary Nebula	50 kyr	hot core emits UV radiation, gas flouresces
White Dwarf	→ ∞	No fusion - cool down

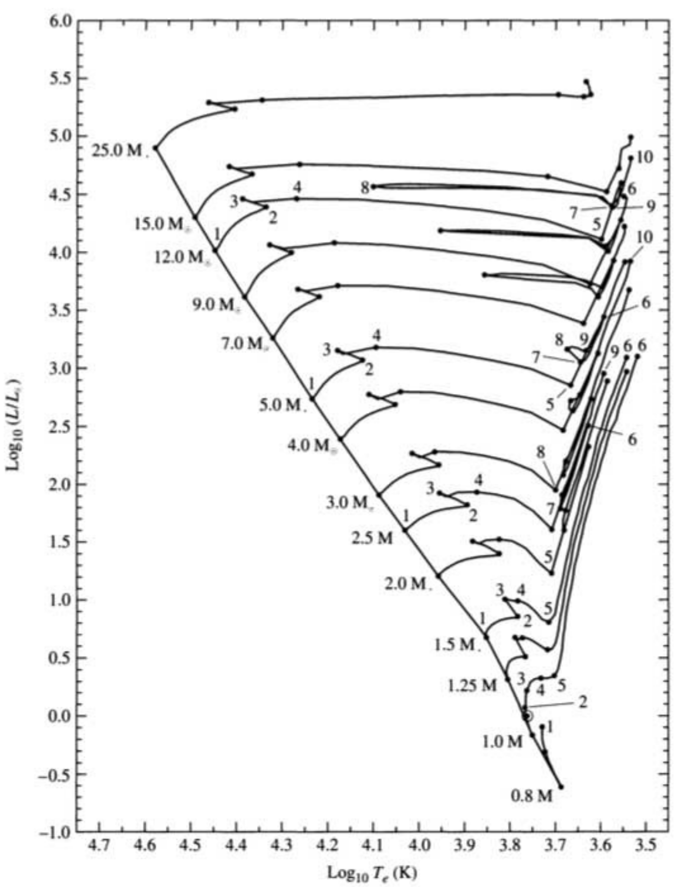

Fig. 20 Main sequence and post main sequence evolution of stars.

Carrol and Ostlie Fig 13.1