Stars and their fates

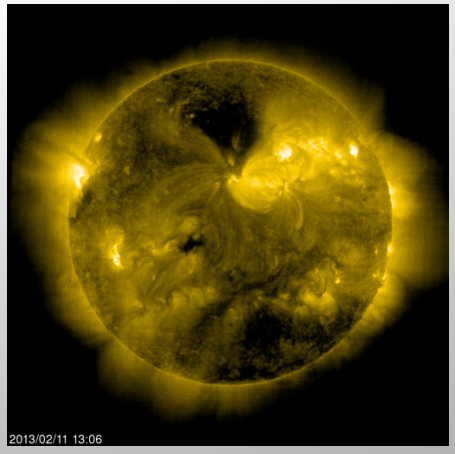
- stars form in regions of dense molecular gas (H_2), nearby example Orion nebula
- initial masses vary widely: 0.1 – 100 Solar masses
- high mass stars are rare, but very luminous

Stars *form* when no forces are strong enough to overcome gravity

Escape velocity from surface of the Sun:

$$v_{esc} = \sqrt{\frac{2GM}{R}}$$

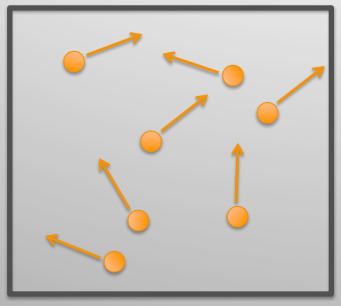
About 600 km per second



If nothing opposed gravity, Sun would collapse at about this speed at the surface

"Free-fall time" less than 20 minutes!

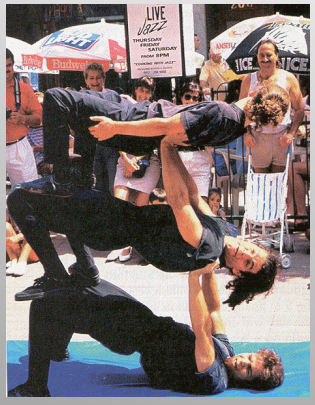
What supports the Sun against gravity?



gas pressure – due to random motions of particles in a hot gas

Kinetic energy is proportional to the temperature, so hotter gas has more pressure

What supports the Sun against gravity?



gas pressure *gradient* – Sun is hotter and denser at the center than near the surface

How "main sequence" stars work

- held up against gravity by an equilibrium between gravity and a pressure gradient

This equilibrium is stable:

- on short time scales – if we "squeeze" a normal star pressure gradient increases more than gravity… it springs back
- on longer time scales – as energy leaks out nuclear reactions generate more, so core remains hot

How long will the Sun live?

Recall: fusion of H to He releases 0.7% of the rest mass energy of the hydrogen

Let's say 10% of the Sun's mass is hydrogen close enough to the core to fuse

Energy available:

$$E = mc^2$$
$$= 0.1 \times 0.007 \times 2 \times 10^{30}\ \text{kg} \times \text{c}^2$$
$$= 1.26 \times 10^{44}\ \text{Joules}$$

How long will the Sun live?

Solar luminosity is 3.8 x 10^{26} Joules per second

Sun can keep going for about:

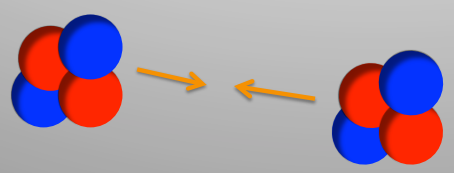
$$\frac{1.26 \times 10^{44}\ \text{Joules}}{3.8 \times 10^{26}\ \text{Joules / s}} = 3.3 \times 10^{17}\ \text{s}$$

10 billion years…

What happens next?

Hydrogen fuel runs out… gravity starts to win:

- core contracts
- temperature goes *up*



collisions of He nuclei become violent enough to lead to fusion (to carbon, oxygen)

Shorter phase: less energy, higher luminosity

What happens next?

Helium fuel runs out… gravity starts to win:

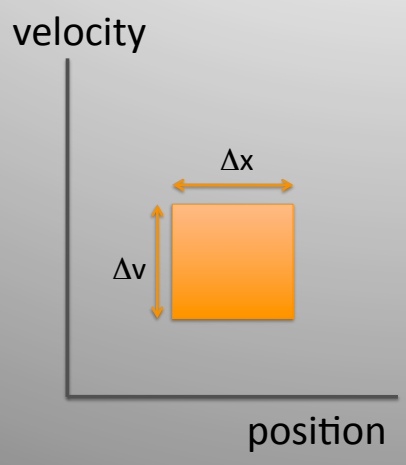
- core contracts
- temperature goes *up*

enough for carbon, oxygen to fuse… route to supernova explosions, neutron stars, black holes

degeneracy pressure stops the contraction, form a *white dwarf* (fate of the Sun)

Degeneracy pressure

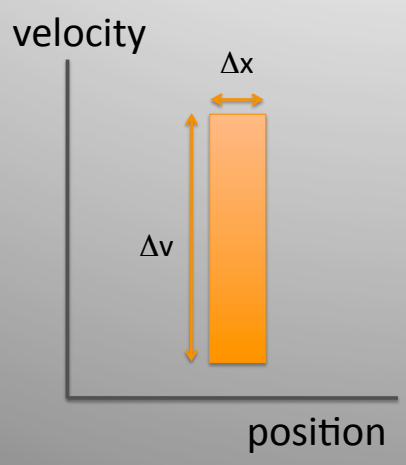
Two types of quantum effects



Uncertainty principle: we cannot know or measure both the position and velocity of a particle to arbitrary precision

Degeneracy pressure

Two types of quantum effects



Uncertainty principle: make Δx small by squeezing particle into small volume, Δv becomes large

But velocity (or energy) of particles is what gives a gas pressure

Degeneracy pressure

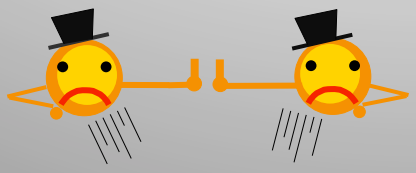
How this works depends on whether the particles are fermions or bosons

Enrico Fermi: fermions include electrons, neutrons, protons

Satyendra Bose: bosons include photons

Degeneracy pressure

Exclusion Principle – no two fermions can occupy the same quantum state (a "quantum state" = position and momentum / velocity)



If fermions are forced to occupy similar positions (high density), random velocities rise

Higher pressure

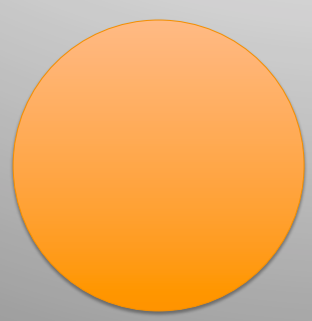
Degeneracy pressure

Purely quantum mechanical effect:

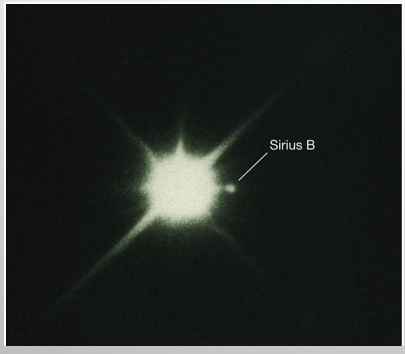
- depends on density *only*, temperature does not affect pressure
- star supported by degeneracy pressure does not need an energy source to keep the temperature (and hence pressure) up to resist gravity

Fate of the Sun

White dwarf star supported against gravity by electron degeneracy pressure

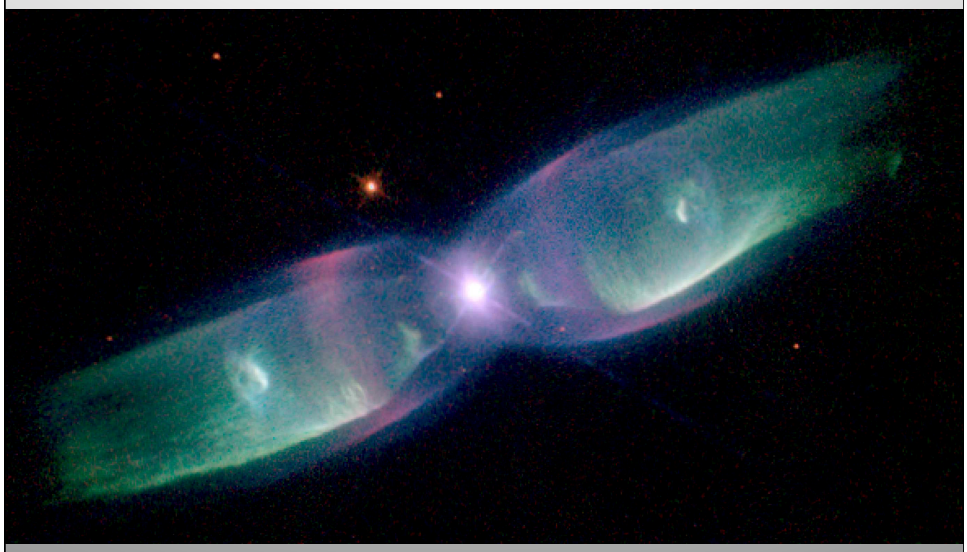


- mass ~0.6 Solar masses
- carbon / oxygen
- radius ~9000 km
- density ~10^9 kg / m^3



Observe white dwarfs as compact objects that cool over time

Where does the rest of the mass go?



…blows away in a planetary nebula