AST 301
Introduction to Astronomy

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AST 301 (Lacy), course website

Topics for this week

Describe the reactions in the proton-proton chain.

How does Einstein's equation, $E = m c^2$, help explain how nuclear reactions generate energy?

Describe how neutrinos allow us to observe the interior of the Sun, and say what was found.

Describe the ideas of thermal and hydrostatic equilibrium for a star.

How are flux (or apparent brightness), luminosity, and distance of a star related?

How do we measure flux and distance of a star?

How do we measure temperatures and masses of stars?

How do we use the Hertzsprung-Russell diagram to make sense of the temperatures and luminosities of stars?

Energy from the Sun

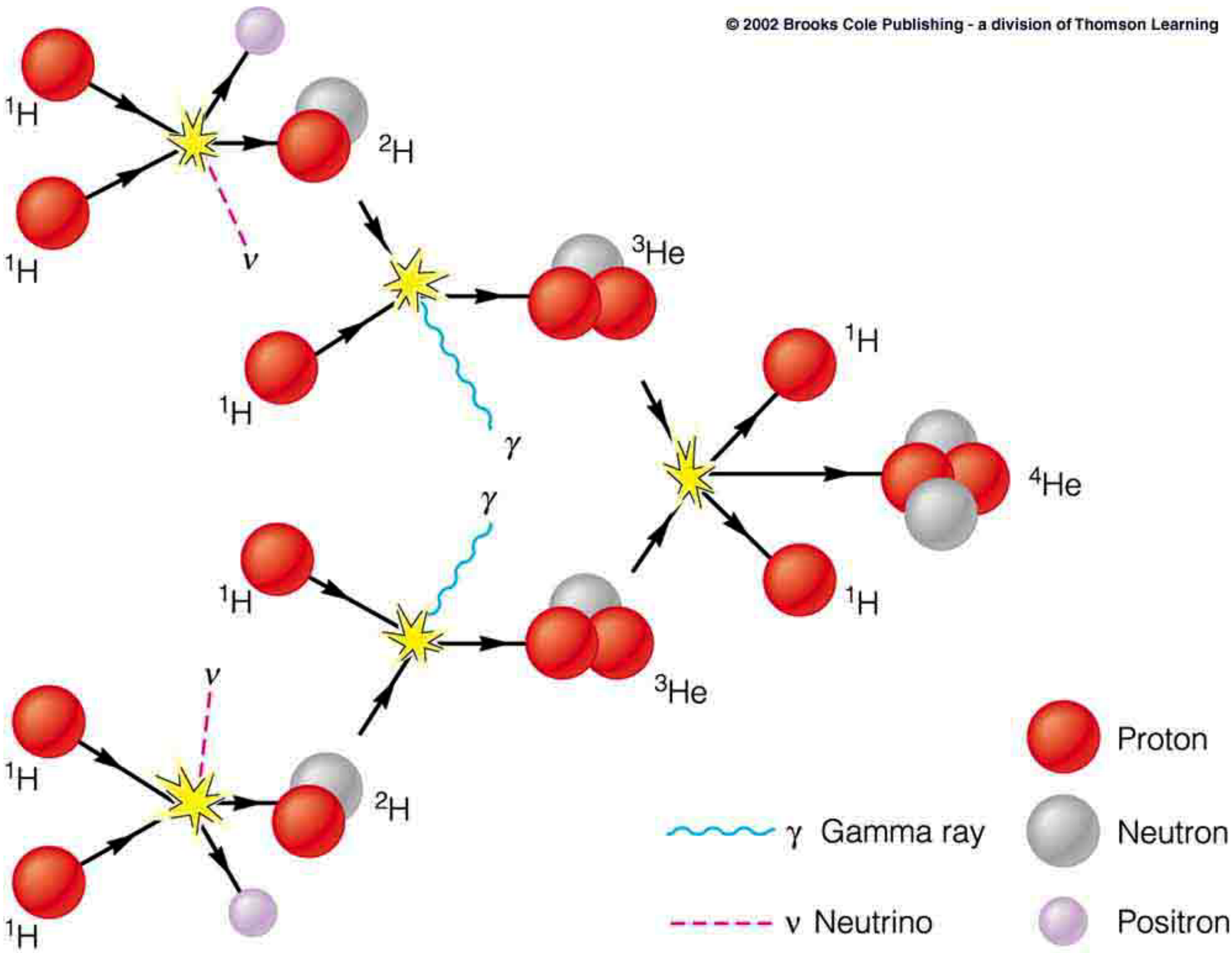
The Sun radiates tremendous amount of energy from its surface. Where does this energy come from?

Nuclear fusion inside the Sun generates energy while fusing hydrogen nuclei to make helium nuclei.

The reaction chain is referred to as the proton-proton chain because the first reaction is the fusion of two protons.

The best way to explain how nuclear reactions generate energy is to note that a helium atom has less mass than the 4 hydrogen atoms that were fused to make it.

Einstein's famous equation, $E = m c^2$, says that mass can be converted into energy (or energy into mass) and to calculate the energy generated by destroying a mass m you multiply m by the square of the speed of light.


1H
1H
2H
ν
1H
3He
γ
1H
4He
1H
γ
1H
3He
ν
1H
2H
1H
Proton
γ Gamma ray
Neutron
ν Neutrino
Positron

Masses and Energies

electron	e^-	9×10^{-31} kg	511 keV
proton	p^+	1836 e^-	938.3 MeV
neutron	n	1839 e^-	939.6 MeV
deuteron	d^+	3669 e^-	1875 MeV
helium	α^{++}	7292 e^-	3727 MeV

$n \rightarrow p^+ + e^- + \bar{\nu} + 0.8$ MeV

$n + \nu \rightarrow p^+ + e^- + 0.8$ MeV

$p^+ \rightarrow n + e^+ + \nu - 1.8$ MeV

$p^+ + p^+ \rightarrow p^+ + n + e^+ + \nu - 1.8$ MeV $\rightarrow d^+ + e^+ + \nu + 1.4$ MeV

$4p^+ \rightarrow \alpha^{++} + 2e^+ + 2\nu + 26.6$ MeV

The rate of fusion

If we know the rate of energy generation, and the amount of energy generated for each helium nucleus made, we can calculate the rate at which helium nuclei are made.

helium nuclei made / second

$$= \frac{\text{energy made / second}}{\text{energy made / helium nucleus made}}$$

Quiz

A 100 Watt light bulb uses 100 Joules (10^2 J) of electrical energy each second. (1 Watt = 1 Joule / second)

A typical photon from a light bulb has about 10^{-19} J of energy.

How many photons does a 100 W light bulb emit each second?

A. 10^{-21}

B. 10^{-17}

C. 10^{17}

D. 10^{21}

Fusion of hydrogen to make helium

1 hydrogen atom: 1.673×10^{-27} kg

4 hydrogen atoms: 6.693×10^{-27} kg

1 helium atom: 6.646×10^{-27} kg

Mass lost: 0.047×10^{-27} kg (0.7% of 6.693×10^{-27})

Energy created = Mass lost x c^2:

4.29×10^{-12} J / He atom formed

Total power (energy radiated per second) from Sun:

3.90×10^{26} J / s

Helium atoms formed / s = (Energy / s) / (Energy / He atom):

9.09×10^{37} He atoms formed / s

Mass destroyed / s = (Energy generated / s) / c^2:

4.33×10^{9} kg / s = 4.33×10^{6} tonnes / s

Is it ‘Just a Theory’?

Fusion only occurs very close to the center of the Sun.

How can we be sure this is how the Sun generates energy?

The neutrinos created when protons became neutrons and positrons during fusion are very unlikely to collide with anything while leaving the Sun.

When they get to the Earth they can cause neutrons to become protons and electrons.

Since 1965 Ray Davis and others have been observing the solar neutrinos through the conversion of neutrons into protons in a tank of dry cleaning fluid (C_2Cl_4) in a gold mine in South Dakota.

He received the Nobel prize in Physics for this work.

Detection of Solar Neutrinos

$n + \nu \rightarrow p^+ + e^-$

$^{37}Cl + \nu \rightarrow {}^{37}Ar + e^-$

…with a half-life of 34 days

$^{37}Ar + e^- \rightarrow {}^{37}Cl + \nu + 0.82$ MeV

By bubbling Ar through the tank of cleaning fluid every week or so, the ^{37}Ar can be collected and measured through its radioactive decay.

But the number of neutrinos detected is only about 1/3 the number expected.

What happened to the other neutrinos?

Is there less nuclear fusion in the Sun than we thought?

Neutrino Oscillations

The favored explanation for the lack of solar neutrinos is that they changed to something else before getting to Davis's tank of dry cleaning fluid.

There are 3 families of leptons (light-weight particles):

electron	e^-	ν_e
muon	μ^-	ν_μ
tau	τ^-	ν_τ

Just like there are 3 families of quarks:

u	d
s	c
t	b

Maybe some of the electron neutrinos turn into the other types on their way here.

Quantum Field Theory

Neutrinos can transform from one type into another if the neutrinos formed from electrons, muons, and taus are not the mass eigenstates (the normal modes) of the neutrino field.

Whatever that means.

In any case, our conclusion is that our theory of nuclear fusion generating energy in the Sun is correct, but we had to modify our theories of how neutrinos work.

Cosmic Gall is both well informed and infused by an underlying irritation about the counter-experiential nature of modern physics.

Cosmic Gall
by John Updike

Neutrinos they are very small.
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.
They snub the most exquisite gas,
Ignore the most substantial wall,
Cold-shoulder steel and sounding brass,
Insult the stallion in his stall,
And, scorning barriers of class,
Infiltrate you and me! Like tall
And painless guillotines, they fall
Down through our heads into the grass.
At night, they enter at Nepal
And pierce the lover and his lass
From underneath the bed – you call
It wonderful; I call it crass.

that about 10^{14} neutrinos from the Sun and 10^{3} neutrinos in cosmic rays pass through our bodies each second.

Their elusiveness is part of their fascination. In the anthropometric vocabulary that lurks in the literature of nuclear physics, neutrinos feature as 'ghosts', 'poltergeists' and 'phantoms' — to say nothing of the 'personalities' they are accorded in physicists' conversations.

Updike opens with a nursery rhyme or limerick sentence, and then bounces through the poem with a series of rapid repetitions — mass, pass, glass, gas, class, lass, crass, all, ball, hall, wall, stall, tall, fall, call and even Nepal. The apparent randomness of his examples highlights the lack of discrimination and extreme disinterestedness of the wandering neutrinos.

We sense a perverse degree of relish for the neutrinos' detachment from our daily realities, our Earth-bound perceptions and engrossing passions — and those of the stallions in their stalls. "Dustmaids down a drafty hall" is a suggestively rich image, relating to no known job description but clear in meaning by analogy to dustmen.

But should physicists really like the poem? It

Equilibriums in stars

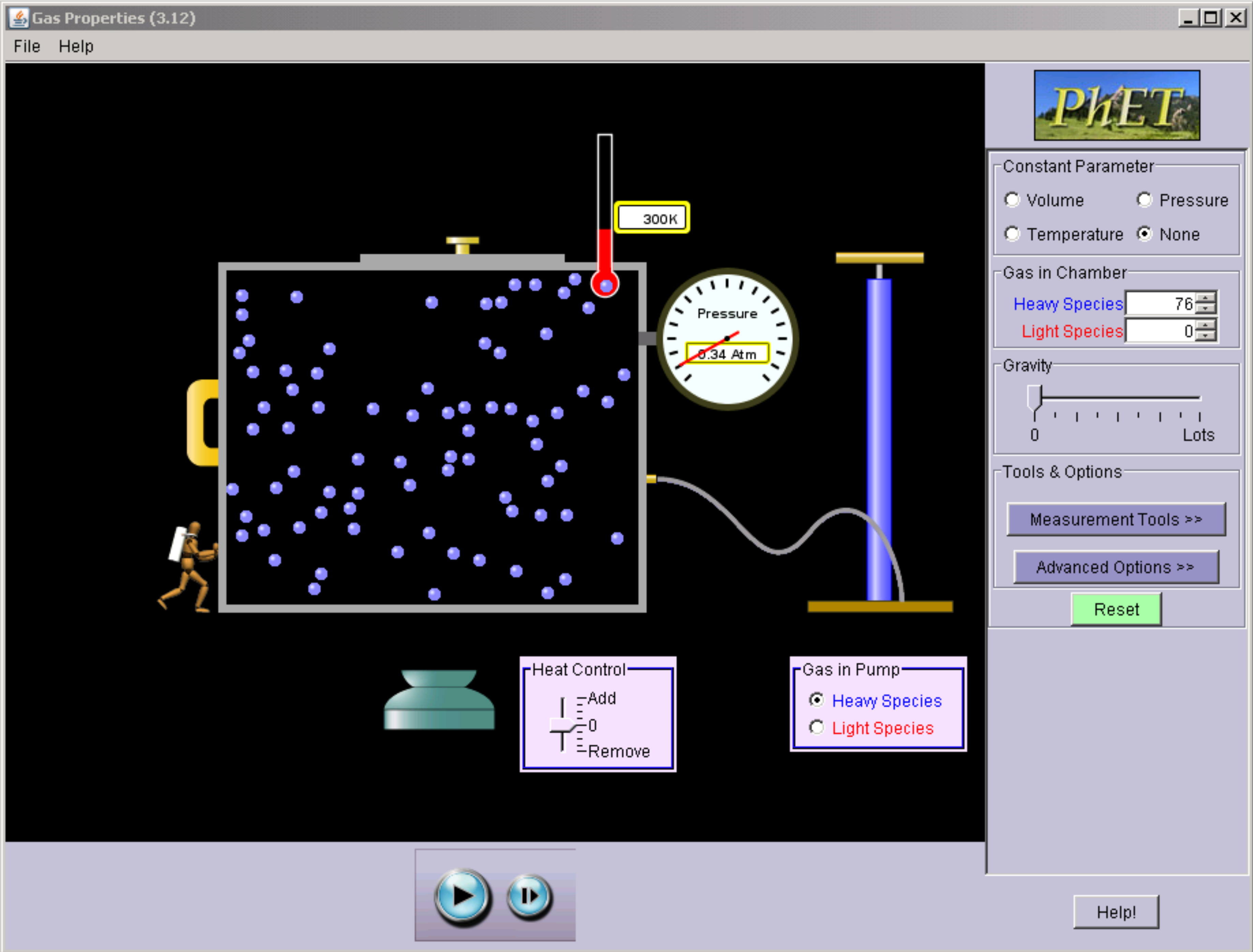
The idea of thermal equilibrium said that the Earth must radiate as much energy into space as it absorbs in sunlight. Otherwise it would change temperature.

For a star to be in thermal equilibrium, it must radiate as much energy into space as it is generating by nuclear fusion.

Stars are also in hydrostatic equilibrium.

For a star to be in hydrostatic equilibrium, the pressure at any point in the star must be right to support the weight of what's above that point.

Pressure is the force per unit area that a gas exerts on its surroundings.



Gas Properties (3.12)
File
Help
300K
Pressure
0.34 Atm
Heat Control
Add
0
Remove
Gas in Pump
Heavy Species
Light Species
Constant Parameter
Volume
Pressure
Temperature
None
Gas in Chamber
Heavy Species
76
Light Species
0
Gravity
0
Lots
Tools & Options
Measurement Tools >>
Advanced Options >>
Reset
Help!

Gas properties

Temperature is a measure of how much energy of motion gas atoms have (how fast they move).

Pressure is the force the gas atoms exert on their surrounding as they bounce off of the walls.

Pressure is proportional to the number of atoms in the box (actually the density, or number of atoms per unit volume).

Pressure is also proportional to the temperature of the gas (because fast moving atoms hit the walls harder and more often).

Squeezing a gas increases both its density and its temperature.

Gravity makes the gas settle toward the bottom of the box, so the pressure is higher toward the bottom.

This is an example of hydrostatic equilibrium.

More on hydrostatic equilibrium

We usually describe hydrostatic equilibrium by saying that the pressure at any point in a star must be right to support the weight of what's above that point.

What if the pressure was too high inside a star?

The star will expand, which decreases the pressure, until pressure is right to support the weight.

This happens quickly, in about an hour.

More on thermal equilibrium

When a star is in thermal equilibrium, the rate of energy generation by fusion equals the rate of energy loss by radiation from the surface of the star.

The rate of fusion depends strongly on temperature, because the protons must be moving fast to get close enough together so they can be attracted by the strong force before their electrical repulsion pushes them apart.

If the center of a star is too hot, fusion will run faster than energy is being radiated from the surface.

But the high temperature will cause high pressure, which will cause the star to expand. And since the star is a gas, when it expands it cools.

So fusion slows down.

Until its rate is right to generate the energy lost by radiation.