A very high resolution image of the center of the Omega nebula (Messier 17) star-forming region. Glowing gas clouds, opaque lanes of interstellar dust, and newborn stars are visible. The rose color comes from hydrogen gas ionized by ultraviolet radiation produced by the bluest, hottest, most massive young stars embedded in the nebula.
Hertzsprung-Russell diagram

Note: Star sizes are not to scale.
• How do astronomers study the gas and dust between the stars, called the interstellar medium?
• How do stars form from the interstellar medium?
• How do stars maintain their stability?
• How do the stars make energy?
• How do the luminosities and lifetime of stars depend on their masses?
The space between the stars is not completely empty, but filled with very dilute gas and dust, producing some of the most beautiful objects in the sky.

We are interested in the interstellar medium because:

a) Dense interstellar clouds are the birth place of stars.

b) Dark clouds alter and absorb the light from stars behind them.
In astronomy, the interstellar medium (ISM) is the matter that exists in the space between the star systems in a galaxy. This matter includes gas in ionic, atomic, and molecular form, as well as dust and cosmic rays. It fills interstellar space and blends smoothly into the surrounding intergalactic space.
# Section 10-1 Stellar Structure

## Table 10-1 The Four Laws of Stellar Structure

<table>
<thead>
<tr>
<th>Law</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Conservation of mass</td>
<td>Total mass equals the sum of the masses in all the layers.</td>
</tr>
<tr>
<td>II. Conservation of energy</td>
<td>Total luminosity equals the sum of energy generated in all of the layers.</td>
</tr>
<tr>
<td>III. Hydrostatic equilibrium</td>
<td>The weight on each layer is balanced by the pressure in that layer.</td>
</tr>
<tr>
<td>IV. Energy transport</td>
<td>Energy moves from hot to cool regions by conduction, radiation, or convection.</td>
</tr>
</tbody>
</table>
The Laws of Conservation of Mass and Energy

• The first two laws of stellar structure have some thing in common—they are both what astronomers and physicists call conservation laws.

• They state that certain things cannot be created out of nothing or vanish into nothing.
  – Such conservation laws are powerful aids to help you understand how nature works.
The law of conservation of mass is a basic law of nature that can be applied to the structure of stars. It states that the total mass of a star must equal the sum of the masses of its shells. This is like saying the weight of a cake must equal the sum of the weight of its layers.
The law of conservation of energy is another basic law of nature.

It states that the amount of energy flowing out of the top of a layer in the star must be equal to the amount of energy coming in at the bottom plus whatever energy is generated within the layer.

That means that the energy leaving the surface of the star—its luminosity—must equal the sum of the energies generated in all the layers inside the star.
Total luminosity equals the sum of energy generated in all the layers.
**Luminosity** - how much energy the stars emit.

- Absolute visual magnitude refers to visible light.
- However, Luminosity is the total output of energy — including all types of radiation.
  - Hot stars emit a great deal of ultraviolet radiation that you can’t see.
  - Cool stars emit plenty of infrared radiation.
Hydrostatic Equilibrium

• In a star that is stable, the deeper layers must support the weight of all the layers above.

• As the inside of a star is made up of gas, the weight pressing down on a layer must be balanced by the gas pressure in the layer.
  • If the pressure is too low, the weight from above will compress and push down the layer.
  • If the pressure is too high, the layer will expand and lift the layers above.

This balance between weight and pressure is called hydrostatic equilibrium
Hydrostatic Equilibrium

Outward pressure force must exactly balance the weight of all layers above everywhere in the star.

This condition uniquely determines the interior structure of the star.

This is why we find stable stars on such a narrow strip (Main Sequence) in the Hertzsprung-Russell diagram.
Hydrostatic Equilibrium

Imagine a star’s interior composed of individual shells.

Within each shell, two forces have to be in equilibrium with each other:

- Outward pressure from the interior
- Gravity, i.e. the weight from all layers above
Energy Transport

- The surface of a star radiates light and heat into space—and would quickly cool if that energy were not replaced.
- As the inside of the star is hotter than the surface, energy must flow outward to the surface, where it radiates away.
  - This flow of energy through each shell determines its temperature—which, as you have learned, determines how much weight that shell can balance.
Energy Transport

• The law of energy transport states that energy must flow from hot regions to cooler regions by conduction, convection, or radiation.

• Question: On a cold day, your house is nice and warm, you open the door and you feel cold air
Energy Transport

Question:

On a cold day, your house is nice and warm, you open the door and you feel cold air. This is because

a. The cold air from out side is coming in
b. The warm air from inside is going out
Energy Transport

Energy generated in the star’s center must be transported to the surface.

Inner layers of the sun:

Radiative energy transport

Outer layers of the sun (including photosphere):

Convection
Energy Transport

• Radiation is the principal means of energy transport in the interiors of most stars.
  • Photons are absorbed and reemitted in random directions over and over as energy works its way from the hot interior toward the cooler surface.
Stellar Structure

Energy generation via nuclear fusion

Energy transport via convection

Energy transport via radiation

Flow of energy

Temperature, density and pressure decreasing

Basically the same structure for all stars with approx. 1 solar mass or less.
Energy Transport

- The figure shows a cross-section of the sun in which zones of radiative and convective energy transport are indicated.
  - Interior – due to high Temperature the gas is very transparent: radiation
  - Nearer surface gas is more opaque: convection
Stellar Models

The structure and evolution of a star is determined by the laws of:

• Hydrostatic equilibrium
• Energy transport
• Conservation of mass
• Conservation of energy

A star’s mass (and chemical composition) completely determines its properties.

That’s why stars initially all line up along the main sequence.
### Processes of Nuclear Energy

<table>
<thead>
<tr>
<th>Process</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fission</strong></td>
<td>A nucleus of large mass number splits into two smaller nuclei</td>
</tr>
<tr>
<td><strong>Fusion</strong></td>
<td>Two light nuclei fuse to form a heavier nucleus</td>
</tr>
</tbody>
</table>

- Large amounts of energy are released in either case.
Hydrogen Fusion

• You can symbolize this process with a simple nuclear reaction:

\[ 4 \, ^1H \rightarrow ^4He + \text{energy} \]

– \(^1H\) represents a proton, the nucleus of a hydrogen atom.
– \(^4He\) represents the nucleus of a helium atom.
– The superscripts indicate the total number of protons and neutrons in each nucleus.
Fusion
All main-sequence stars fuse hydrogen into helium to generate energy.

- The sun and smaller stars fuse hydrogen by the proton–proton chain.
- Upper-main-sequence stars, more massive than the sun, fuse hydrogen by a more efficient process called the CNO (carbon-nitrogen-oxygen) cycle.
In stars slightly more massive than the sun, a more powerful energy generation mechanism than the PP chain takes over.

The CNO Cycle
Neutrino is a nearly massless particle that has no electric charge, is very hard to detect because they rarely interact with ordinary matter. They easily pass through the entire Earth as if it weren’t there.

According to the model of fusion in the Sun, nearly $10^{38}$ solar neutrinos are produced every second – 100 billion neutrinos should pass through every sq. cm of your body/sec.

The Davis solar neutrino experiment consists of a huge tank of 100,000 gal of dry cleaning fluid in a deep mine in S. Dakota. Every now and then a $\nu$ hits a chlorine atom and converts one of its neutrons into a proton and creates a radioactive argon – only 1/3 as many as expected were detected.
The Source of Stellar Energy

solar neutrinos

Recall from our discussion of the sun:

Stars produce energy by nuclear fusion of hydrogen into helium

In the sun, this happens primarily through the proton-proton (PP) chain.

This process is efficient at temperatures above 10,000,000 K.
The Sudbury Neutrino Observatory is a globe 12 meters in diameter containing water rich in deuterium in place of hydrogen. Buried 6800 feet deep in an Ontario mine, it can detect all three flavors of neutrinos and confirms that neutrinos oscillate.
Nobelpriset i fysik 2015

Takaaki Kajita
Super-Kamiokande Collaboration
University of Tokyo, Kashiwa, Japan

Arthur B. McDonald
Sudbury Neutrino Observatory Collaboration
Queen’s University, Kingston, Canada

"för upptäckten av neutrinooscillationer, som visar att neutriner har massa"
"for the discovery of neutrino oscillation"

Observation of neutrinos in the atmosphere

- Cosmic ray
  - Muon neutrinos
  - Switches to tau neutrinos (oscillation)
  - Cosmic ray (mainly protons)
  - Nucleus in the atmosphere
  - Muon neutrinos created
  - Atmosphere
Pressure Temperature thermostat

How does the pressure-temperature thermostat control the nuclear reaction inside stars?

How does the contraction of a gas cloud increase its temperature?
Upper-main-sequence O stars are the most massive stars.

The lower-main-sequence red dwarfs are the lowest-mass stars.

Note: Star sizes are not to scale.
The more massive a star is → The more Luminous
The Life of Main Sequence Stars

Stars gradually exhaust their hydrogen fuel.

In this process of aging, they are gradually becoming brighter, evolving off the zero-age main sequence.
### The Lifetimes of Stars on the Main Sequence

6. Why is there a lower limit to the mass of a main-sequence star?

#### Table 9-2 | Main-Sequence Stars

<table>
<thead>
<tr>
<th>Spectral Type</th>
<th>Mass (Sun = 1)</th>
<th>Luminosity (Sun = 1)</th>
<th>Years on Main Sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>05</td>
<td>40</td>
<td>405,000</td>
<td>$1 \times 10^6$</td>
</tr>
<tr>
<td>B0</td>
<td>15</td>
<td>13,000</td>
<td>$11 \times 10^6$</td>
</tr>
<tr>
<td>A0</td>
<td>3.5</td>
<td>80</td>
<td>$440 \times 10^6$</td>
</tr>
<tr>
<td>F0</td>
<td>1.7</td>
<td>6.4</td>
<td>$3 \times 10^9$</td>
</tr>
<tr>
<td>G0</td>
<td>1.1</td>
<td>1.4</td>
<td>$8 \times 10^9$</td>
</tr>
<tr>
<td>K0</td>
<td>0.8</td>
<td>0.46</td>
<td>$17 \times 10^9$</td>
</tr>
<tr>
<td>M0</td>
<td>0.5</td>
<td>0.08</td>
<td>$56 \times 10^9$</td>
</tr>
</tbody>
</table>
Why does a star's life expectancy depend on its mass?

How Does a Star Form and What Determines Its Life Span?

How long a star lives depends on its mass. Small-mass stars use up their fuel more slowly than large-mass stars, so they have much longer lives. While small-mass stars may live for as long as 200 billion years, a large mass star may live only about ten million years.

Life of a Star

A star's lifetime depends on its mass.

Explain- the yellow star has much less mass than the blue star and so will live longer.

Explain why.
Interstellar Medium

- Nebula N44: Roughly 40 young stars are inflating a bubble of hot gas inside the nebula from which they formed.

- Horsehead Nebula: Dusty foreground gas silhouetted against glowing gas illuminated by hot, young stars.

- Visual-wavelength image: Young star embedded in the nebula.
Figure 10.10

- **Interstellar cloud**: A cloud of gas and dust between the stars.

- **Star**: The bright object in the image.

- **Telescope**: A device used to observe distant objects in space.

- **Path of blue photons**: The path of photons with shorter wavelengths.

- **Path of red photons**: The path of photons with longer wavelengths.

**No stars visible through center of Barnard 86, “The Black Cloud.”**

**Infrared image reveals many stars hidden behind the nebula.**

**Stars seen through edges of nebula dimmed and reddened.**
How is the blue color of a reflection nebula related to the blue color of the daytime sky?
In the star cluster called the Pleiades, the hottest stars are B6, not hot enough to ionize hydrogen in the interstellar medium. Instead, the brightest stars produce a reflection nebula as their light is scattered from interstellar dust.

Dark nebulae are denser clouds of gas and dust that obstruct the view of more distant stars. Some are generally round, but others are twisted and distorted, as shown at the left, suggesting that even when there are no nearby stars to ionize the gas or produce a reflection nebula, there are breezes and currents pushing through the interstellar medium.

Large dark nebulae obstruct the view of more distant stars and form holes and rifts along the Milky Way. The Great Rift extends from Cygnus to Sagittarius.
The wispiness of the infrared cirrus reveals the turbulence of the interstellar medium.

About 450 ly in diameter, the cavity has been inflated by many supernova explosions.

A nearby cavity only 110 ly in diameter formed by the explosion of a single star.
Shocks Triggering Star Formation

A shock wave (red) approaches an interstellar gas cloud.

The shock wave passes through and compresses the cloud.

Shock Wave Triggers Star Formation

Shock wave passes.

The densest parts of the cloud become gravitationally unstable.

Contracting regions of gas give birth to stars.
These massive stars were triggered into formation by compression from the formation of earlier stars out of the image to the left.

New stars are forming in these dense clouds because of compression from the stars to the left.

**Figure 10-14 p220**

Location of ancient supernova explosion

Arc of gas compressed by shock wave from supernova.

Star formation triggered by compression.
Observation of star formation

- Protostars less than 0.1% of star’s total lifetime
- Form deep inside dust clouds
- Can be detected with IR
Star Formation in the Orion Nebula

1. The visible Orion Nebula shown below is a pocket of ionized gas on the near side of a vast, dusty molecular cloud that fills much of the southern part of the constellation Orion. The molecular cloud can be mapped by radio telescopes. To scale, the cloud would be many times larger than this page. As the stars of the Trapezium were born in the cloud, their radiation has ionized the gas and pushed it away. Where the expanding nebula pushes into the larger molecular cloud, it is compressing the gas (see diagram at right) and may be triggering the formation of the protostars that can be detected at infrared wavelengths within the molecular cloud.

Hundreds of stars lie within the nebula, but only the four brightest, those in the Trapezium, are easy to see with a small telescope. A fifth star, at the narrow end of the Trapezium, can be visible on nights of good seeing.

The cluster of stars in the nebula is less than 2 million years old. This means the nebula is similarly young.

2. Of all the stars in the Orion Nebula, only one is hot enough to ionize the gas. Only photons with wavelengths shorter than 912 nm can ionize hydrogen. The second hottest stars in the nebula are B1 stars, and they emit only a fraction of this ionizing radiation. The hottest star, however, is an O6 star 30 times the mass of the sun. At a temperature of 40,000 K, it emits plenty of photons with wavelengths short enough to ionize hydrogen. Remove that one star, and the nebula would turn off its emission.
The infrared image from the Spitzer Space Telescope reveals extensive nebulosity surrounding the visible Orion Nebula. Red and orange show the locations of warm dust that has been heated by starlight, green shows hot dust and ionized gas, and blue shows light coming directly from stars.

In this near-infrared image, known among some astronomers as the “Hand of God” image, fingers of gas rush away from the region of the infrared protostars.

The Becklin-Neugebauer object (BN) is a hot B star just reaching the main sequence. It is not detectable at visual wavelengths. The Keistmann-Low nebula (KL) is a cluster of cool, young protostars detectable only in the infrared.

The spectral types of the Trapezium stars are shown here. The gas icons green because of filters used to record the image.

As many as 85 percent of the stars in the Orion Nebula are surrounded by disks of gas and dust. One such disk is seen at the upper right of this Hubble Space Telescope image, magnified in VISIT. Radiation from the nearby hot Trapezium stars is evaporating gas from the disk and driving it away to form an elongated nebula.
Emission and Reflection Nebulae

The hottest star in the Pleiades star cluster is Merope, a B3 star. It is not hot enough to ionize the gas so you see a reflection nebula rather than an emission nebula.

A dusty reflection nebula is located very close to the star Merope above. The glare from the star is caused by internal reflections in the telescope, but the wispy nature of the nebula is real. The intense light from the star is pushing the dust particles away and may destroy the little nebula over the next few thousand years.