16.1 Stellar Nurseries

Our goals for learning:

- Where do stars form?
- Why do stars form?

Star-Forming Clouds

- Stars form in dark clouds of dusty gas in interstellar space
- The gas between the stars is called the **interstellar medium**

Composition of Clouds

- We can determine the composition of interstellar gas from its absorption lines in the spectra of stars
- 70% H, 28% He, 2% heavier elements in our region of Milky Way

Molecular Clouds

- Most of the matter in star-forming clouds is in the form of molecules (H_2, CO,…)
- These *molecular clouds* have a temperature of 10-30 K and a density of about 300 molecules per cubic cm

Molecular Clouds

- Most of what we know about molecular clouds comes from observing the emission lines of carbon monoxide (CO)

Interstellar Dust

- Tiny solid particles of *interstellar dust* block our view of stars on the other side of a cloud
- Particles are < 1 micrometer in size and made of elements like C, O, Si, and Fe

Interstellar Reddening

- Stars viewed through the edges of the cloud look redder because dust blocks (shorter-wavelength) blue light more effectively than (longer-wavelength) red light

Interstellar Reddening

- Long-wavelength infrared light passes through a cloud more easily than visible light
- Observations of infrared light reveal stars on the other side of the cloud

Observing Newborn Stars

- Visible light from a newborn star is often trapped within the dark, dusty gas clouds where the star formed

Observing Newborn Stars

- Observing the infrared light from a cloud can reveal the newborn star embedded inside it

Glowing Dust Grains

- Dust grains that absorb visible light heat up and emit infrared light of even longer wavelength

Interactive Figure

Glowing Dust Grains

- Long-wavelength infrared light is brightest from regions where many stars are currently forming

Gravity versus Pressure

- Gravity can create stars only if it can overcome the force of thermal pressure in a cloud
- Emission lines from molecules in a cloud can prevent a pressure buildup by converting thermal energy into infrared and radio photons

Mass of a Star-Forming Cloud

- A typical molecular cloud (T~ 30 K, n ~ 300 particles/cm^3) must contain at least a few hundred solar masses for gravity to overcome pressure
- Emission lines from molecules in a cloud can prevent a pressure buildup by converting thermal energy into infrared and radio photons that escape the cloud

Resistance to Gravity

- A cloud must have even more mass to begin contracting if there are additional forces opposing gravity
- Both magnetic fields and turbulent gas motions increase resistance to gravity

Fragmentation of a Cloud

- Gravity within a contracting gas cloud becomes stronger as the gas becomes denser
- Gravity can therefore overcome pressure in smaller pieces of the cloud, causing it to break apart into multiple fragments, each of which may go on to form a star

Fragmentation of a Cloud

- This simulation begins with a turbulent cloud containing 50 solar masses of gas

Fragmentation of a Cloud

- The random motions of different sections of the cloud cause it to become lumpy

Fragmentation of a Cloud

- Each lump of the cloud in which gravity can overcome pressure can go on to become a star
- A large cloud can make a whole cluster of stars

Isolated Star Formation

- Gravity can overcome pressure in a relatively small cloud if the cloud is unusually dense
- Such a cloud may make only a single star

Thought Question

What would happen to a contracting cloud fragment if it were not able to radiate away its thermal energy?

A. It would continue contracting, but its temperature would not change
B. Its mass would increase
C. Its internal pressure would increase

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The First Stars

- Elements like carbon and oxygen had not yet been made when the first stars formed
- Without CO molecules to provide cooling, the clouds that formed the first stars had to be considerably warmer than today's molecular clouds
- The first stars must therefore have been more massive than most of today's stars, for gravity to overcome pressure

Simulation of the First Star

- Simulations of early star formation suggest the first molecular clouds never cooled below 100 K, making stars of ~100M_{Sun}

What have we learned?

- Where do stars form?
  - Stars form in dark, dusty clouds of molecular gas with temperatures of 10-30 K
  - These clouds are made mostly of molecular hydrogen (H_2) but stay cool because of emission by carbon monoxide (CO)
- Why do stars form?
  - Stars form in clouds that are massive enough for gravity to overcome thermal pressure (and any other forms of resistance)
  - Such a cloud contracts and breaks up into pieces that go on to form stars

16.2 Stages of Star Birth

Our goals for learning:

- What slows the contraction of a star-forming cloud?
- What is the role of rotation in star birth?
- How does nuclear fusion begin in a newborn star?

Trapping of Thermal Energy

- As contraction packs the molecules and dust particles of a cloud fragment closer together, it becomes harder for infrared and radio photons to escape
- Thermal energy then begins to build up inside, increasing the internal pressure
- Contraction slows down, and the center of the cloud fragment becomes a **protostar**

Growth of a Protostar

- Matter from the cloud continues to fall onto the protostar until either the protostar or a neighboring star blows the surrounding gas away

Evidence from the Solar System

- The nebular theory of solar system formation illustrates the importance of rotation

Conservation of Angular Momentum

- The rotation speed of the cloud from which a star forms increases as the cloud contracts

Rotation of a contracting cloud speeds up for the same reason a skater speeds up as she pulls in her arms

Flattening

- Collisions between particles in the cloud cause it to flatten into a disk

Collisions between gas particles in cloud gradually reduce random motions

Collisions between gas particles also reduce up and down motions

Spinning cloud flattens as it shrinks

Formation of Jets

- Rotation also causes jets of matter to shoot out along the rotation axis

Jets are observed coming from the centers of disks around protostars

Thought Question

What would happen to a protostar that formed without any rotation at all?

A. Its jets would go in multiple directions
B. It would not have planets
C. It would be very bright in infrared light
D. It would not be round

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From Protostar to Main Sequence

- Protostar looks starlike after the surrounding gas is blown away, but its thermal energy comes from gravitational contraction, not fusion
- Contraction must continue until the core becomes hot enough for nuclear fusion
- Contraction stops when the energy released by core fusion balances energy radiated from the surface—the star is now a *main-sequence star*

Birth Stages on a Life Track

- Life track illustrates star’s surface temperature and luminosity at different moments in time

Assembly of a Protostar

- Luminosity and temperature grow as matter collects into a protostar

Convective Contraction

- Surface temperature remains near 3,000 K while convection is main energy transport mechanism

Radiative Contraction

- Luminosity remains nearly constant during late stages of contraction, while radiation is transporting energy through star

Self-Sustaining Fusion

- Core temperature continues to rise until star arrives on the main sequence

Life Tracks for Different Masses

- Models show that Sun required about 30 million years to go from protostar to main sequence
- Higher-mass stars form faster
- Lower-mass stars form more slowly

What have we learned?

- What slows the contraction of a star-forming cloud?
  – The contraction of a cloud fragment slows when thermal pressure builds up because infrared and radio photons can no longer escape
- What is the role of rotation in star birth?
  – Conservation of angular momentum leads to the formation of disks around protostars

What have we learned?

- How does nuclear fusion begin in a newborn star?
  – Nuclear fusion begins when contraction causes the star's core to grow hot enough for fusion

16.3 Masses of Newborn Stars

Our goals for learning:

- What is the smallest mass a newborn star can have?
- What is the greatest mass a newborn star can have?
- What are the typical masses of newborn stars?

Fusion and Contraction

- Fusion will not begin in a contracting cloud if some sort of force stops contraction before the core temperature rises above 10^7 K.
- Thermal pressure cannot stop contraction because the star is constantly losing thermal energy from its surface through radiation
- Is there another form of pressure that can stop contraction?

Degeneracy Pressure:

Laws of quantum mechanics prohibit two electrons from occupying same state in same place

Thermal Pressure:

Depends on heat content

The main form of pressure in most stars

Degeneracy Pressure:

Particles can’t be in same state in same place

Doesn’t depend on heat content

Brown Dwarfs

- Degeneracy pressure halts the contraction of objects with <0.08M_{Sun} before core temperature become hot enough for fusion
- Starlike objects not massive enough to start fusion are **brown dwarfs**

Brown Dwarfs

- A brown dwarf emits infrared light because of heat left over from contraction
- Its luminosity gradually declines with time as it loses thermal energy

Brown Dwarfs in Orion

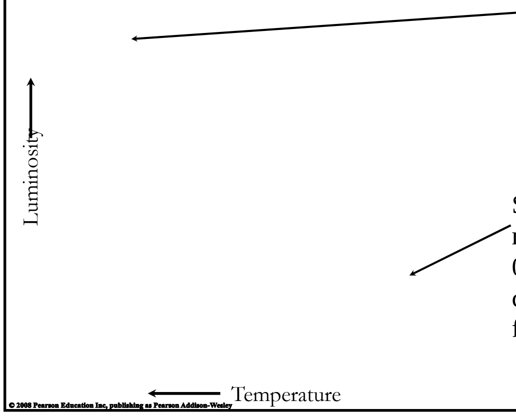
- Infrared observations can reveal recently formed brown dwarfs because they are still relatively warm and luminous

Radiation Pressure

- Photons exert a slight amount of pressure when they strike matter
- Very massive stars are so luminous that the collective pressure of photons drives their matter into space

Upper Limit on a Star's Mass

- Models of stars suggest that radiation pressure limits how massive a star can be without blowing itself apart
- Observations have not found stars more massive than about $150M_{\text{Sun}}$



Stars more massive than $150M_{Sun}$ would blow apart

Stars less massive than $0.08M_{Sun}$ can't sustain fusion

What are the typical masses of newborn stars?

Demographics of Stars

- Observations of star clusters show that star formation makes many more low-mass stars than high-mass stars

What have we learned?

- What is the smallest mass a newborn star can have?
  - Degeneracy pressure stops the contraction of objects $<0.08M_{Sun}$ before fusion starts
- What is the greatest mass a newborn star can have?
  - Stars greater than about $150M_{Sun}$ would be so luminous that radiation pressure would blow them apart

What have we learned?

- What are the typical masses of newborn stars?
  - Star formation makes many more low-mass stars than high-mass stars