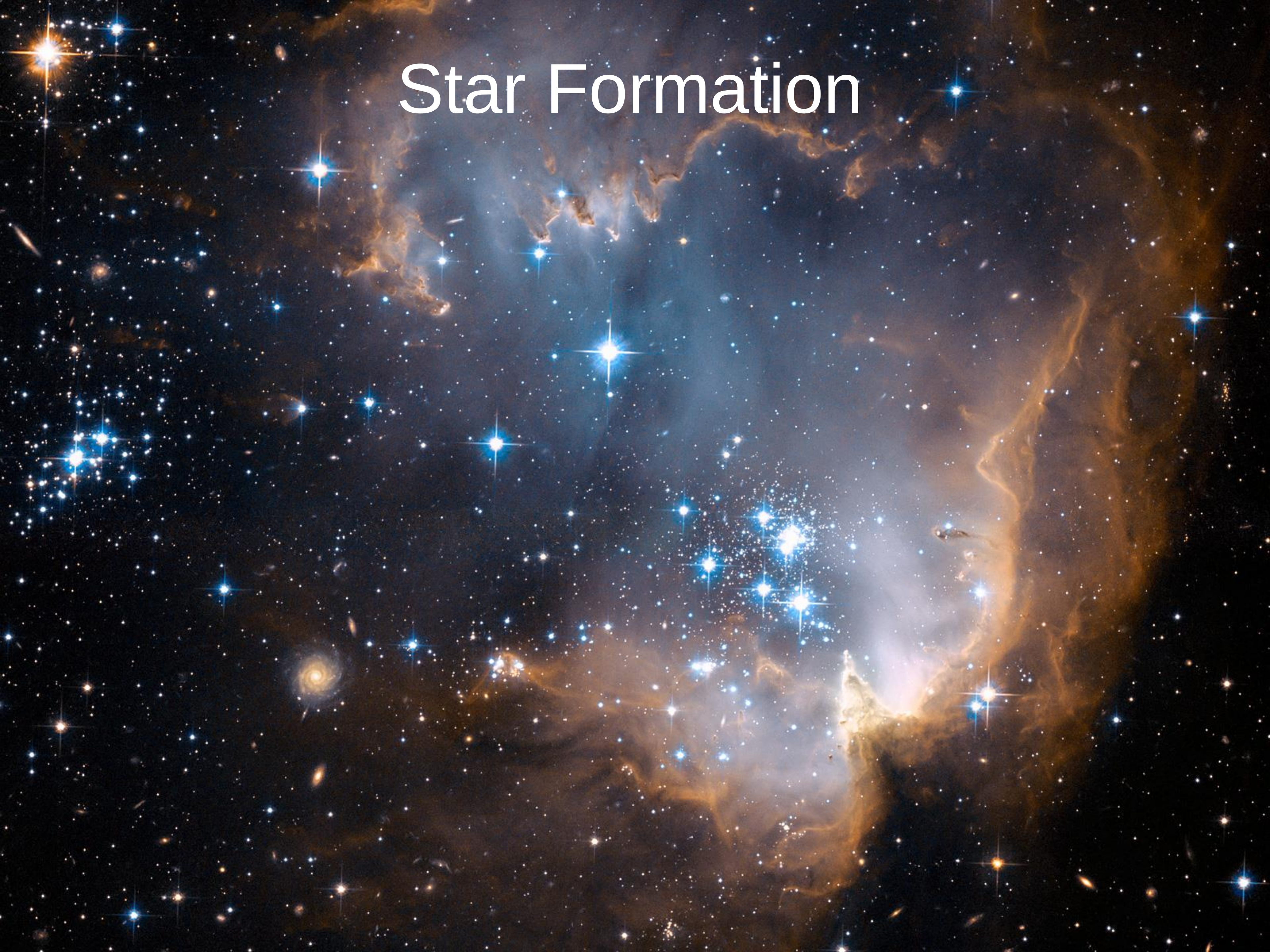
Star Formation



Chapter 19: Star Formation

- Star forming regions
- Stages of the formation of Sun-like Stars:
  - Interstellar Clouds
  - Collapse of a Fragment
  - Protostars
  - Evolution of Protostars
  - Newborn Stars and the Main Sequence
- Stars of Other Masses
- Shock Waves as a Triggering Mechanism
- Star Clusters

Star Forming Regions: NGC 3582

- Most stars are formed in relatively dense, dark, giant molecular clouds. Such regions are known as **Stellar Nurseries**. This is NGC 3582 (10,000 ly).

Star Forming Regions

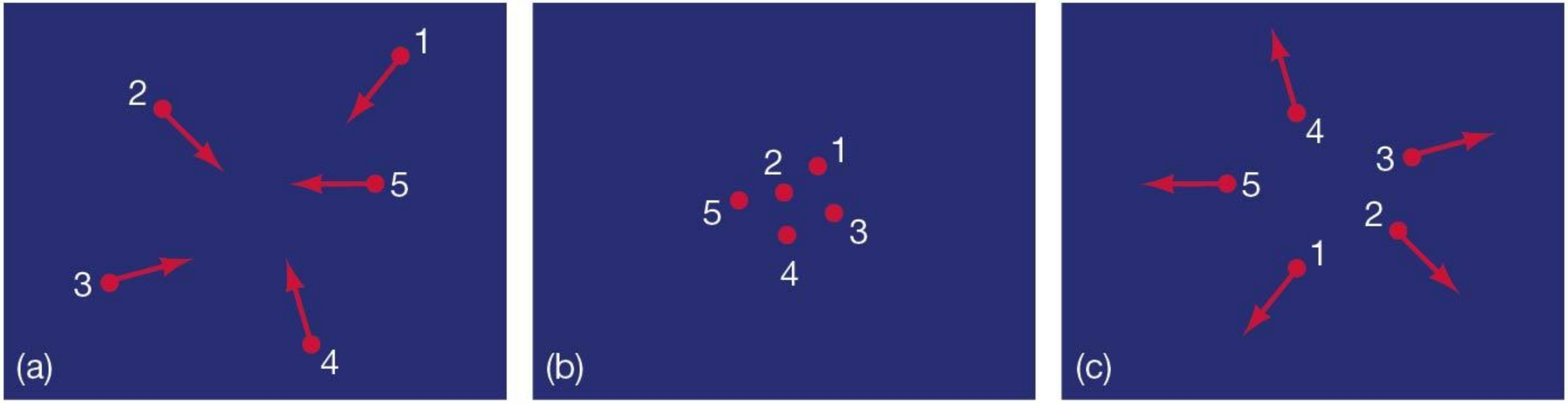
- NGC 3582 is located in the Carina-Sagittarius spiral arm of our Galaxy (ESO in Chile), and extends about 100 (bright) – 1000 ly (darker).

Star Forming Regions: the “Tarantula”

- This star forming region lies in the Large Magellanic Cloud. About 165,000 ly away.

Star Forming Regions

- When looking at just a few atoms, the gravitational force is nowhere near strong enough to overcome the random thermal motion.
- This is also true of many gas and dust clouds, which have enough pressure to support themselves under gravity.



If more than a few atoms interact, the group would come together, start to slide by, but then pause, and finally contract into a clump.

Star Forming Region

- The temperature determines the average speed of the molecules:

$$v = 157\sqrt{T}$$

- If this velocity is greater than the escape velocity from the cloud, it will escape:

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

and the cloud will evaporate.

- If it is significantly less, the cloud will collapse. For a 2000 solar mass cloud of radius 10 pc we find that $v_{esc} > v$ **if the cloud temperature is 30 K or lower.**

Overall Picture of Star Formation

- Star formation can only happen when a large enough clump of matter forms, begins to attract more matter gravitationally and to contract.
- The process of contraction is called **Gravitational Collapse.**
- As it collapses, gravitational instabilities tend to develop in the interstellar cloud, which begins to fragment.
- The center of each fragment gets hotter as it collapses.
- When the central temperature reaches about 10 million K, fusion begins in the core.

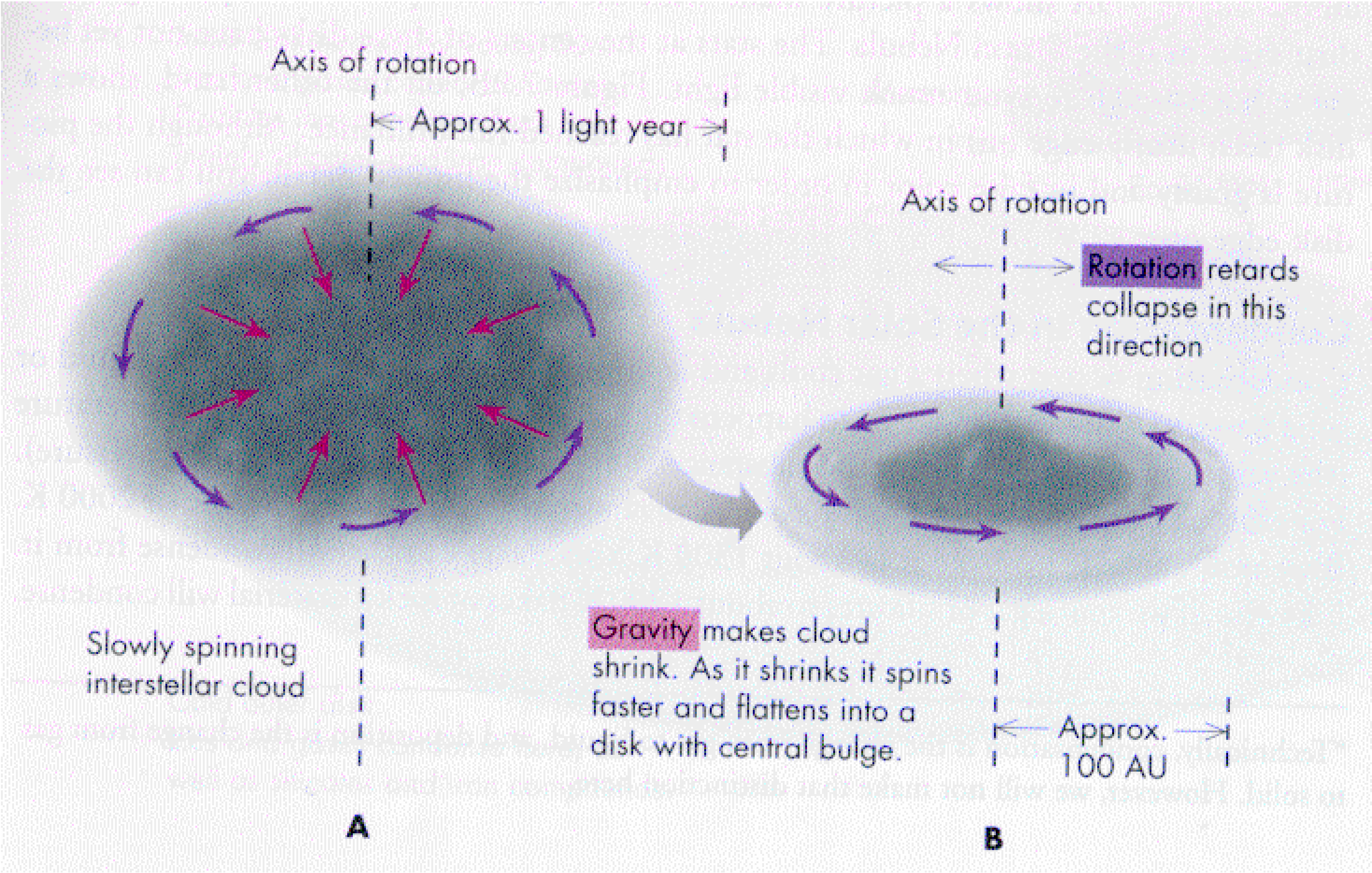
Competitors to Gravitational Collapse

- Gravity is attractive and, on its own, would cause all gas and dust clouds to collapse.
- **Heat**, or the random motion of molecules competes with gravity. The higher the temperature, the higher the pressure preventing collapse.
- **Rotation** will also compete against gravity's inward pull. Rotating clouds develop a bulge in the midsection. As the cloud contracts, it spins faster, the bulge gets larger and the outer edges tend to fly off.
- **Magnetism** tends to distort the clouds as they contract, making them unstable. The fields get stronger as the clouds collapse, so this effect becomes more and more pronounced.

Heat

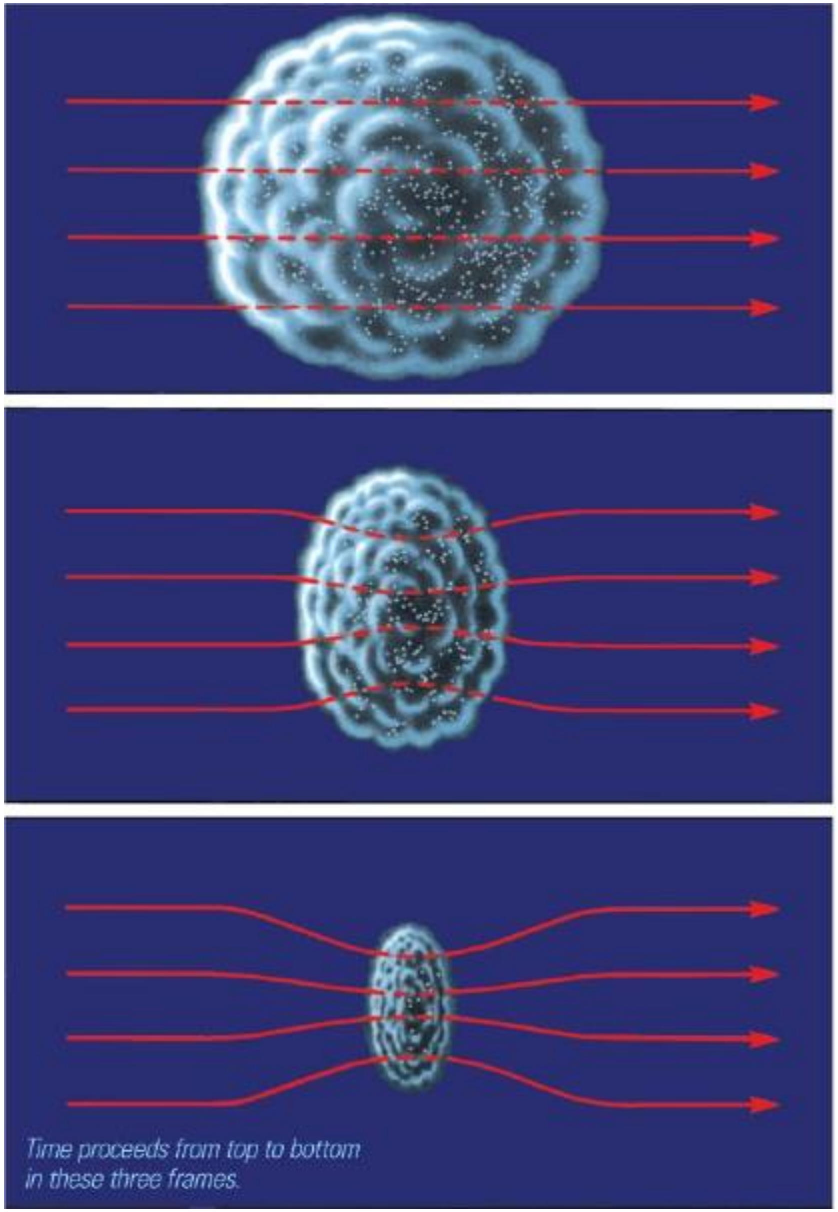
- Small clusters of atoms have insufficient gravity on their own to survive very long.
- Larger clusters of atoms can exert a meaningful gravitational attraction on other particles.
- Gravity gets stronger with mass, so once a **large enough** cluster of atoms forms, the process can “run away”, attracting more and more atoms.
- What’s “large enough” will depend on the temperature of the cloud. The cooler a cloud is the more likely it is for Gravity to dominate.
- Star Formation can only begin once Gravity dominates and a large enough cluster forms.

Rotation


Axis of rotation
Approx. 1 light year
Axis of rotation
Rotation retards collapse in this direction
Slowly spinning interstellar cloud
Gravity makes cloud shrink. As it shrinks it spins faster and flattens into a disk with central bulge.
Approx. 100 AU
A
B

Magnetism

- Magnetism distorts the shape of a gas and dust cloud as it contracts.
- The contraction occurs preferentially along the field lines.
- The magnetic field gets stronger as the cloud collapses.
- This can lead to instabilities that cause the cloud to fragment.



The Formation of Stars Like the Sun

- Stars go through a number of stages in the process of forming from an interstellar cloud.

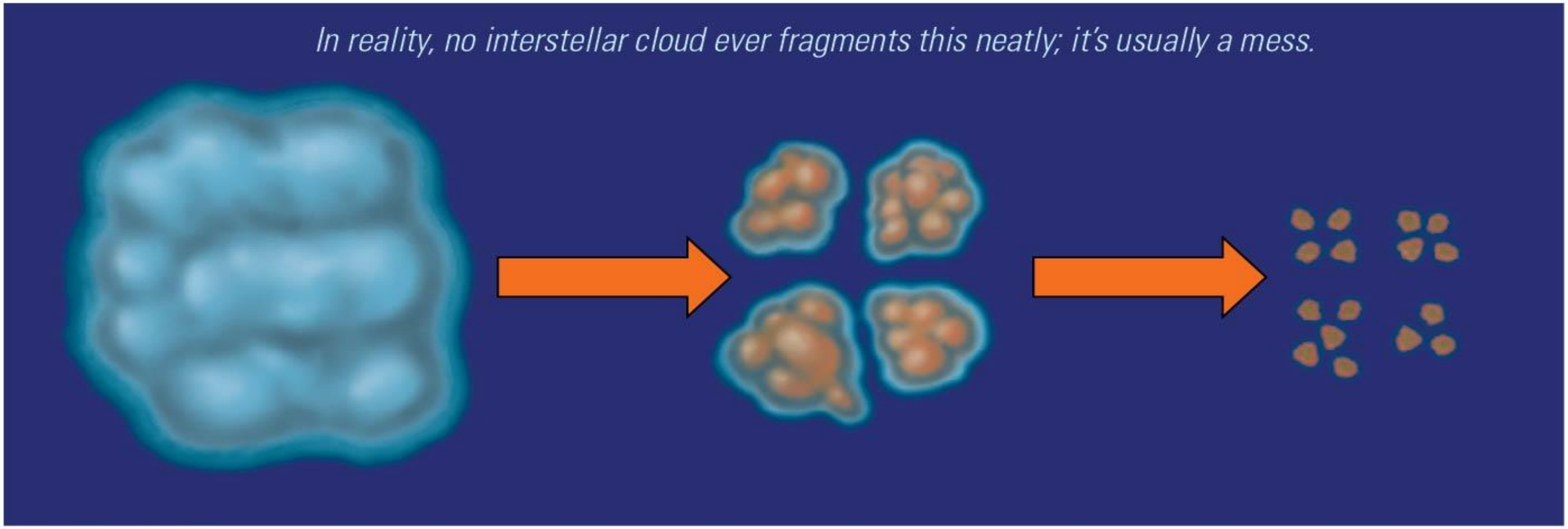
TABLE 11.2 Prestellar Evolution of a Sun-like Star

Stage	Approximate Time to Next Stage (yr)	Central Temperature (K)	Surface Temperature (K)	Central Density (particles/m^3)	Diameter[1] (km)	Object
1	2×10^6	10	10	10^9	10^{14}	Interstellar cloud
2	3×10^4	100	10	10^{12}	10^{12}	Cloud fragment
3	10^{15}	10,000	100	10^{18}	10^{10}	Cloud fragment/protostar
4	10^6	1,000,000	3000	10^{24}	10^8	Protostar
5	10^7	5,000,000	4000	10^{28}	10^7	Protostar
6	2×10^6	10,000,000	4500	10^{31}	2×10^6	Star
7	10^{10}	15,000,000	6000	10^{32}	1.5×10^6	Main-sequence star

[1]For comparison, recall that the diameter of the Sun is 1.4×10^6 km and that of the solar system roughly 1.5×10^{10} km.

Stages of Star Formation

- **Stage 1 (about 2 million years)**: Cold interstellar cloud (10 K – 20 K) containing thousands of solar massed starts to contract, triggered by **condensation** or **shock** or **pressure** wave from a nearby star. As it contracts, the cloud fragments into smaller (a few or tens or hundreds or even thousands of) pieces.



Stages of Star Formation

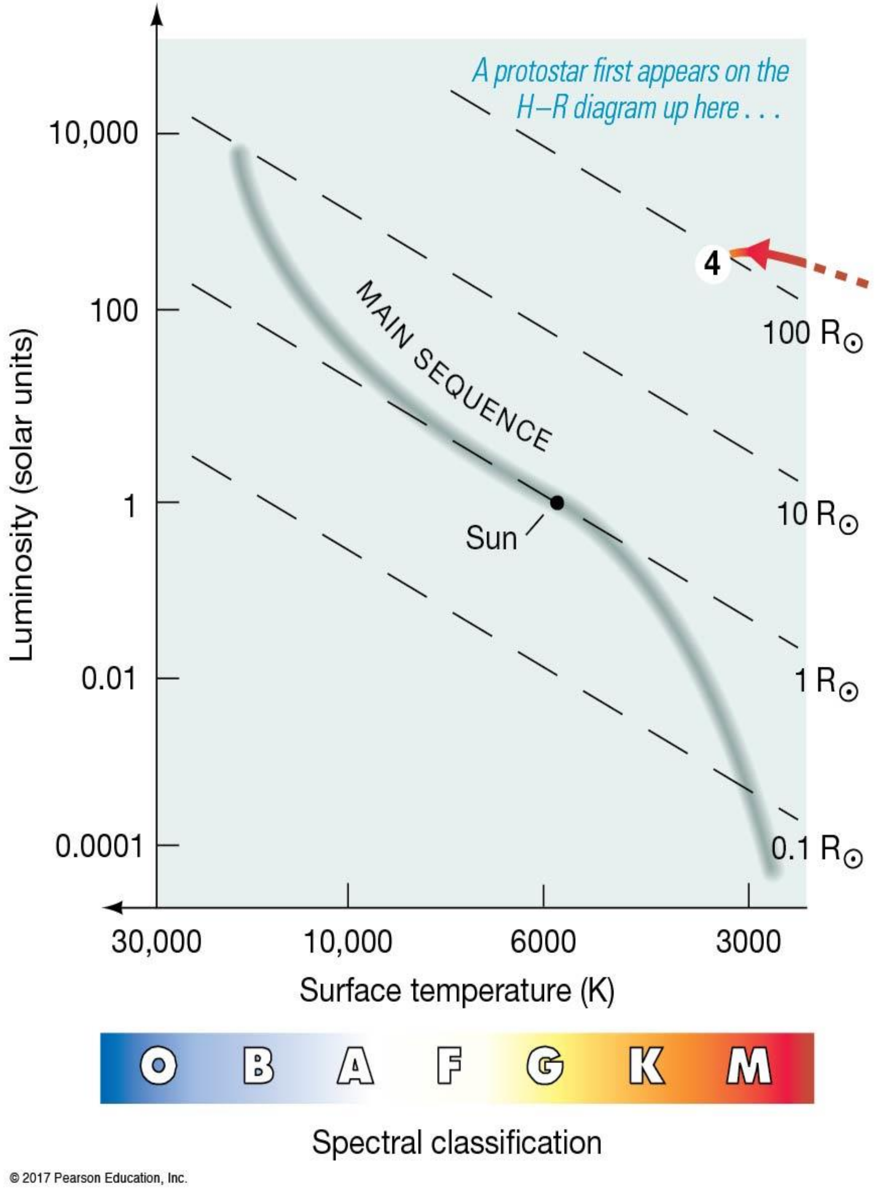
- **Stage 2 (about 30,000 years)**:
  - Individual cloud fragments (a few percent of a parsec across) begin to collapse. No further fragmentation occurs once the density is high enough.
  - The star is transparent enough to radiate out most of the energy produced during the collapse and stays cool. The hottest part is the core, at about 100 K
- **Stage 3 (about 100,000 years)**:
  - The Stage 2 fragment is now about the size of the solar system. The density in high, so energy produced in collapse cannot easily escape the core.
  - The interior of the fragment has begun heating and is about 10,000 K. Its core is now called a **Protostar**.

Stages of Star Formation

- **Stage 4 (about 1 million years)**:
  - About 100,000 years after the fragment first formed.
  - The core temperature reaches 1 million K.
  - The fragment is now a **Protostar**.
  - No fusion yet, but the Protostar is about 1000 times more luminous than the sun.
  - Collapse has led to a size that is now only about 100 times the size of the sun
  - Denser, so collapse slows.
  - The outer fragment flattens into a disk and rotates faster. The matter in the disk will form planets. The disk is called a **Protostellar disk.**
  - Still not in equilibrium and collapse continues…

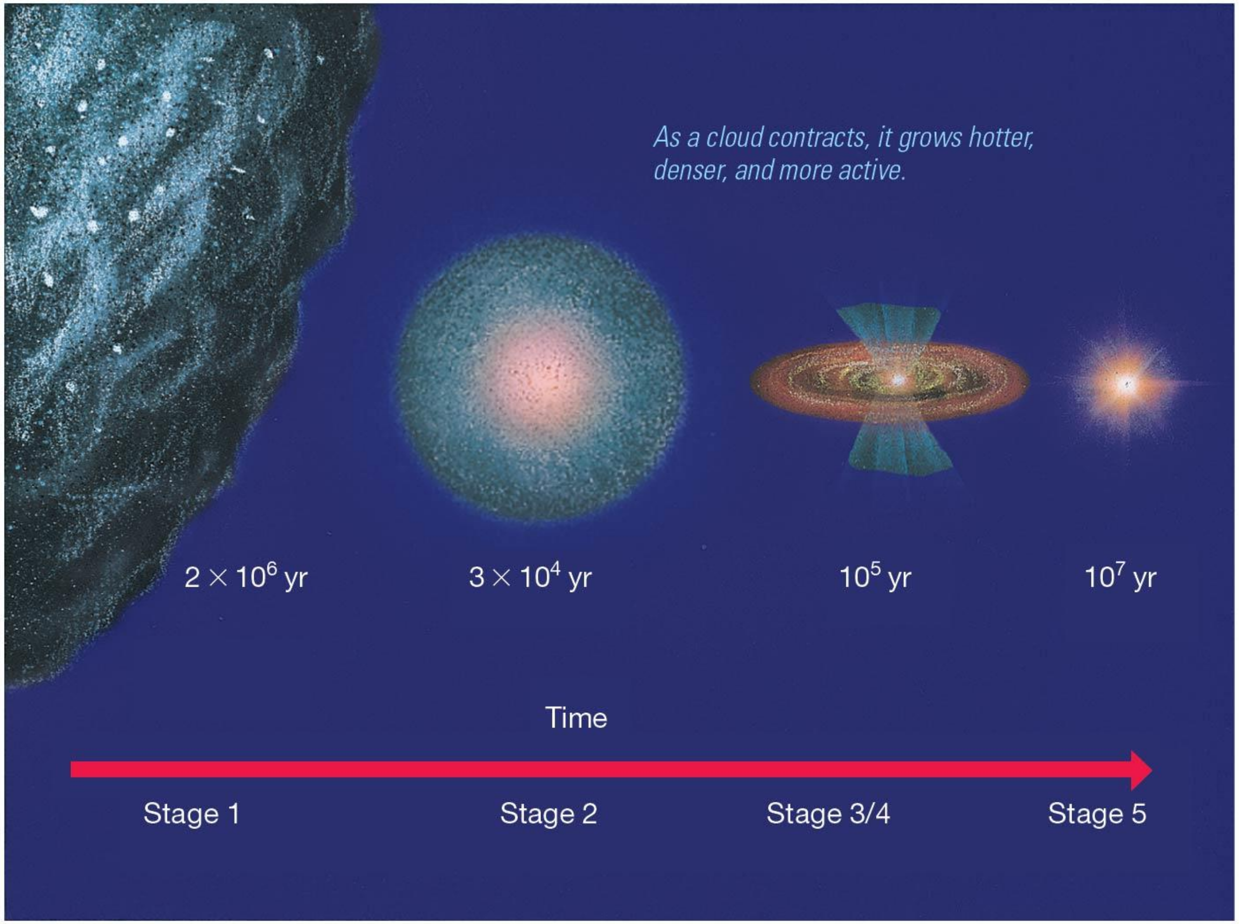
Stages of Star Formation

- The **Protostar** makes its first appearance on the H–R diagram.
- Protostars often exibit strong winds, related to the surface activity on the star.
- These **Protostellar Winds** appear as jets perpendicular to the disk
- Eventually these winds blow the disk away.



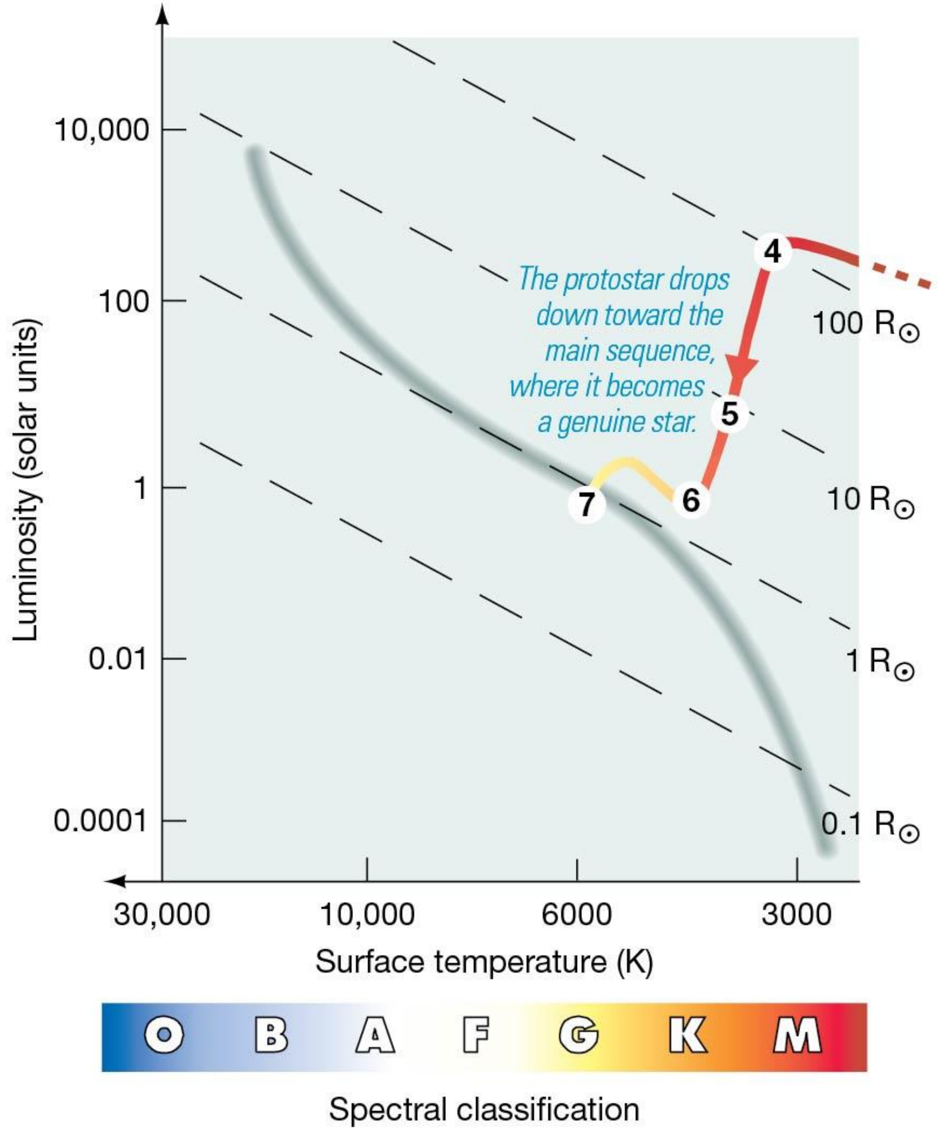
Stages of Star Formation

- Planetary formation has begun, but the protostar is still not in equilibrium—all heating comes from the gravitational collapse. There is no nuclear fusion.



Stages of Star Formation

- The **last stages** can be followed on the H–R diagram.
- **Stage 5 (10 million years):**
  - The Protostar's luminosity decreases even as its temperature rises because it is becoming more compact.
  - Core Temp. about 5 million K (no fusion yet).
  - The contraction rate keeps slowing, so this stage lasts a long time.

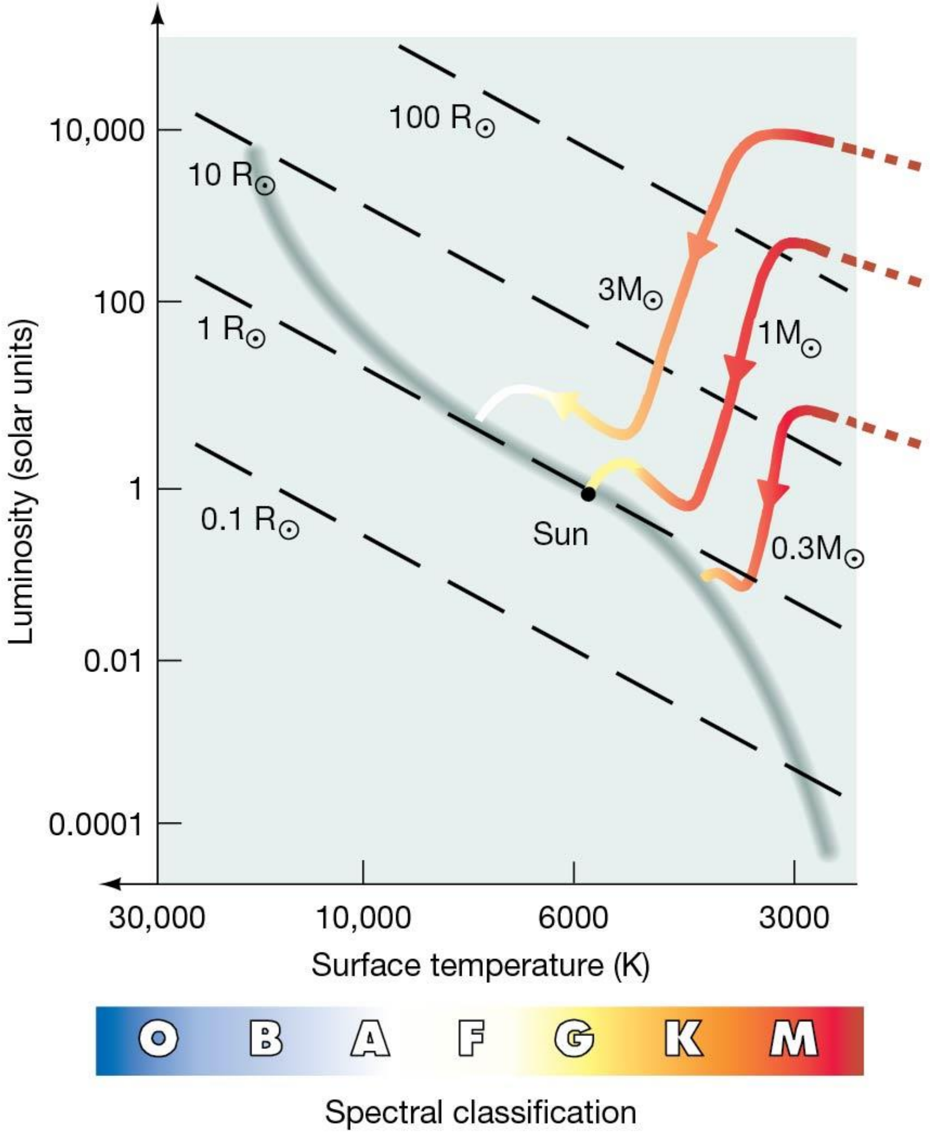


Stages of Star Formation

- **Stage 6 (about 30 million years):**
  - The star contracts to only a few times the size of our sun and the core temperature reaches 10 million K.
  - The surface temperature is approximately 4500 K.
  - Nuclear fusion begins. The protostar has become a star.
  - The star continues to contract and increase in temperature, until it is achieves hydrostatic equilibrium.
- **Stage 7 (about 10 billion years):**
  - From here it takes about 30 million years to reach the main sequence. The star will remain there as long as it has hydrogen to fuse in its core.

Stars of Other Masses

- This H–R diagram shows the **evolutionary tracks** of stars somewhat more and somewhat less massive than the Sun. The shape of the paths is similar, but they wind up in different places on the main sequence.
- (A star reaches main sequence when Hydrogen burning begins in its core.)

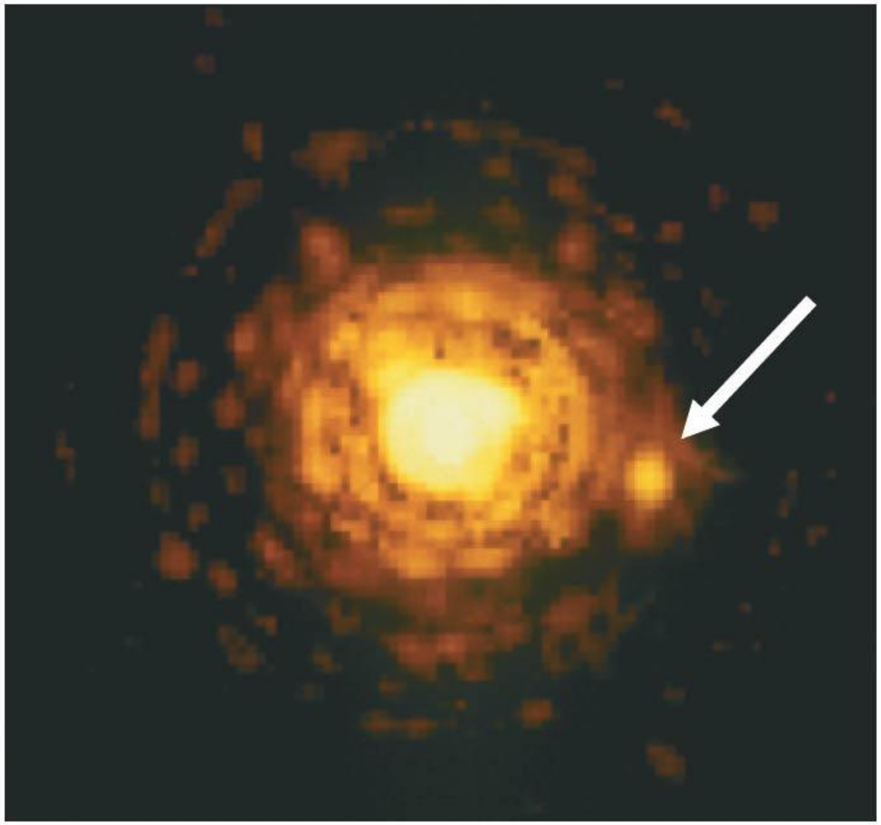


Stars of Other Masses

- The time required for a fragment to reach the main sequence depends on its mass and composition.
- The largest fragments can become O or B type stars in about a million years.
- The smallest end up as **red** or **brown dwarfs**.
  - A **brown dwarf** is a failed star. These fragments are so small that the central temperature never quite gets up to the minimum of 10 million required for fusion. To distinguish them from planets, we require the mass to be at least 12 times the mass of Jupiter.
  - A **red dwarf** is a small and relatively cool star M type star *on the main sequence*.

Evidence: Red and Brown dwarfs

- Brown Dwarfs are very hard to detect because they are at best very dim. This is the binary Gliese 229.



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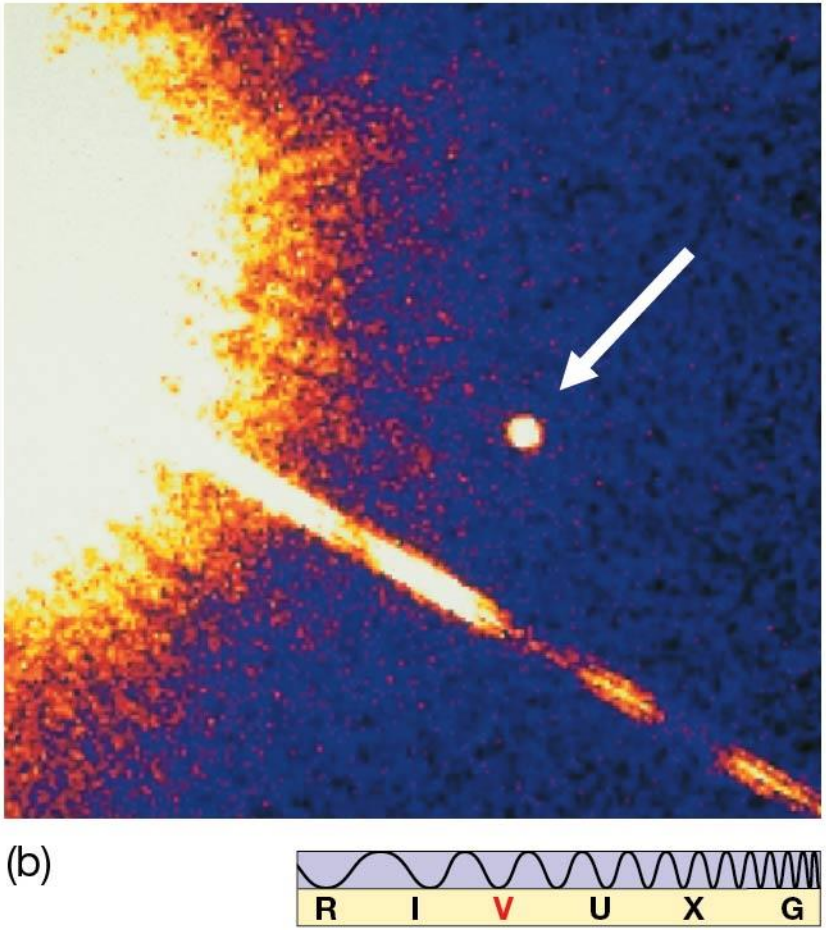

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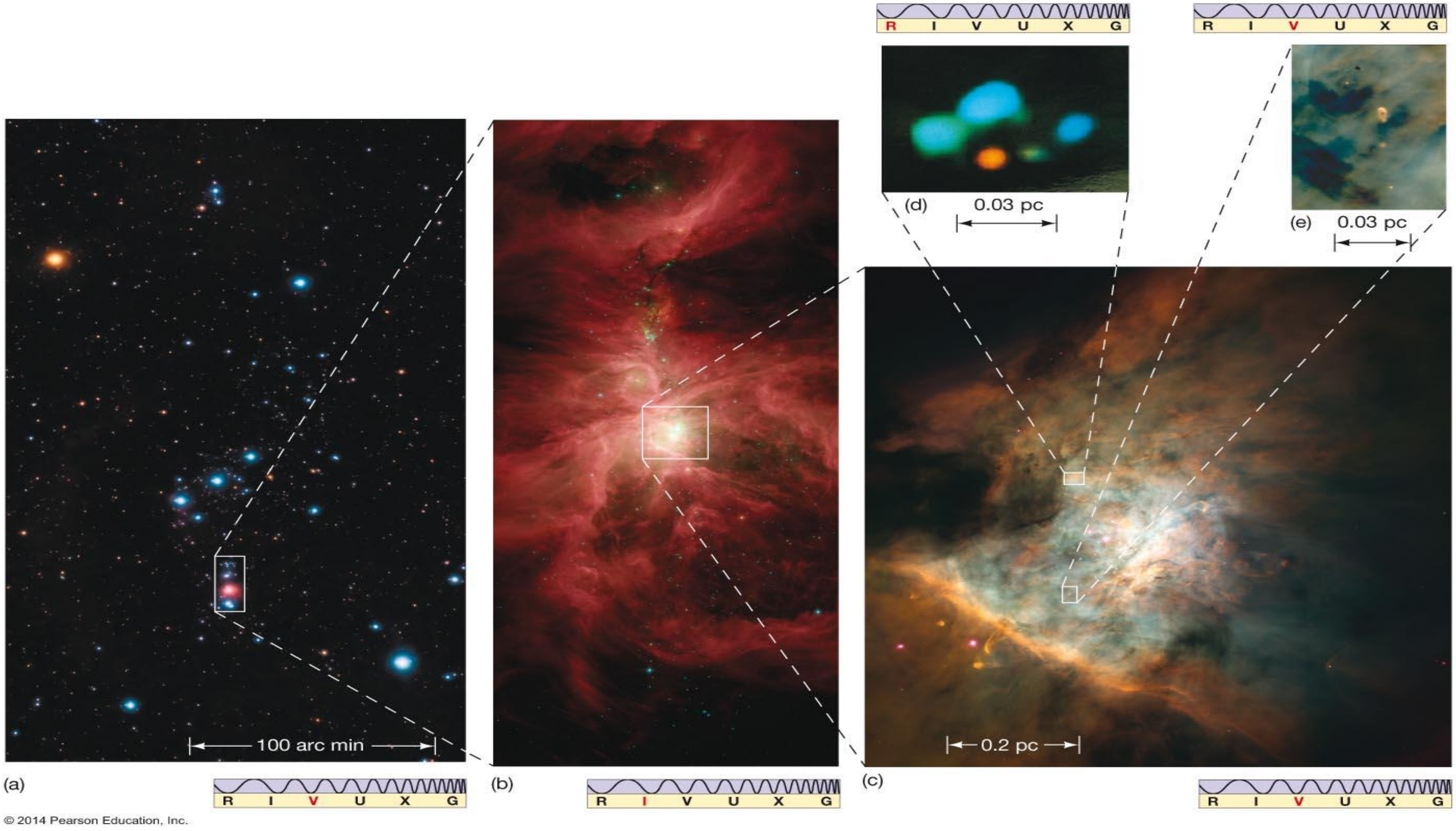
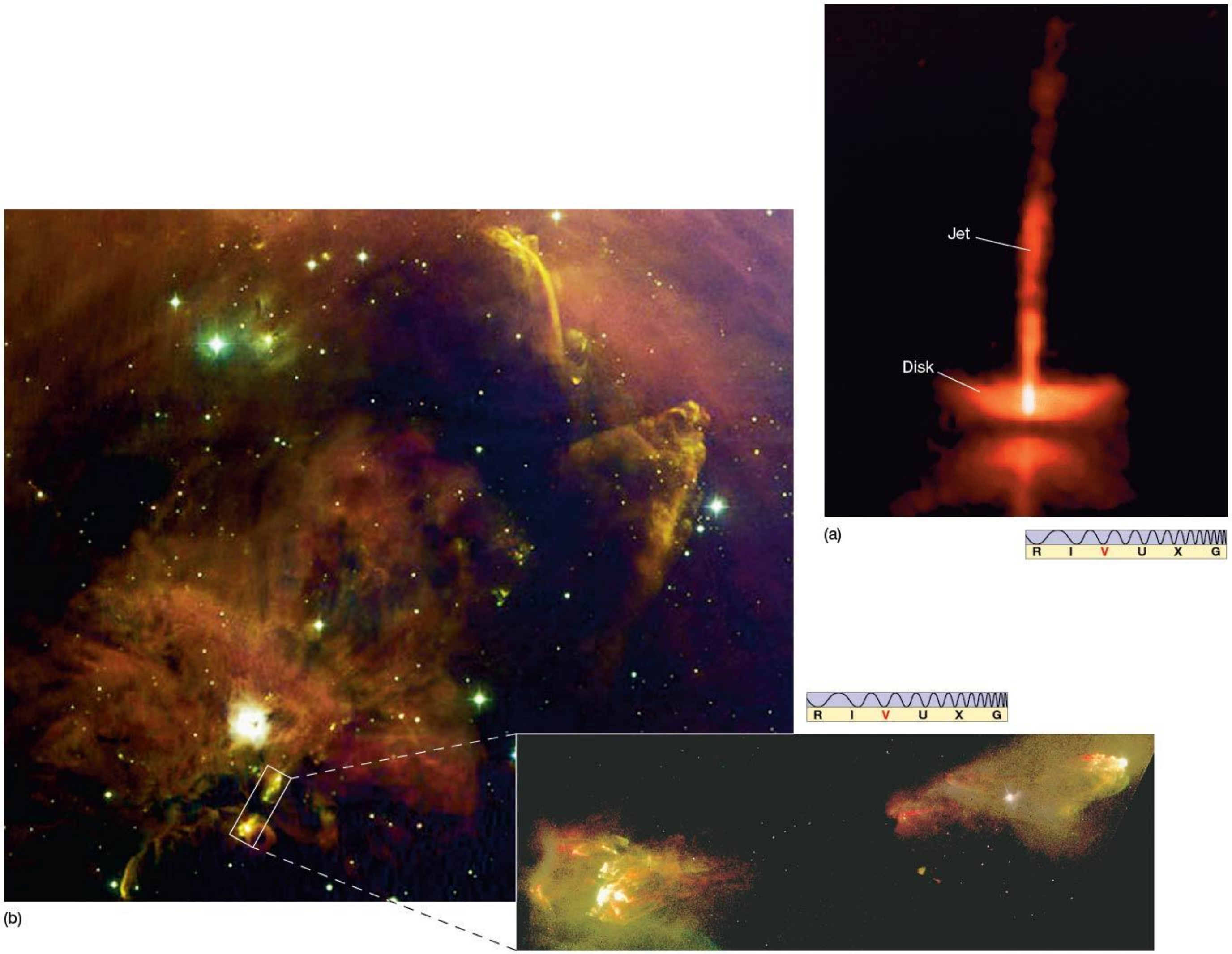
Evidence: Cloud Fragments

- The Orion Nebula shows several contracting fragments:



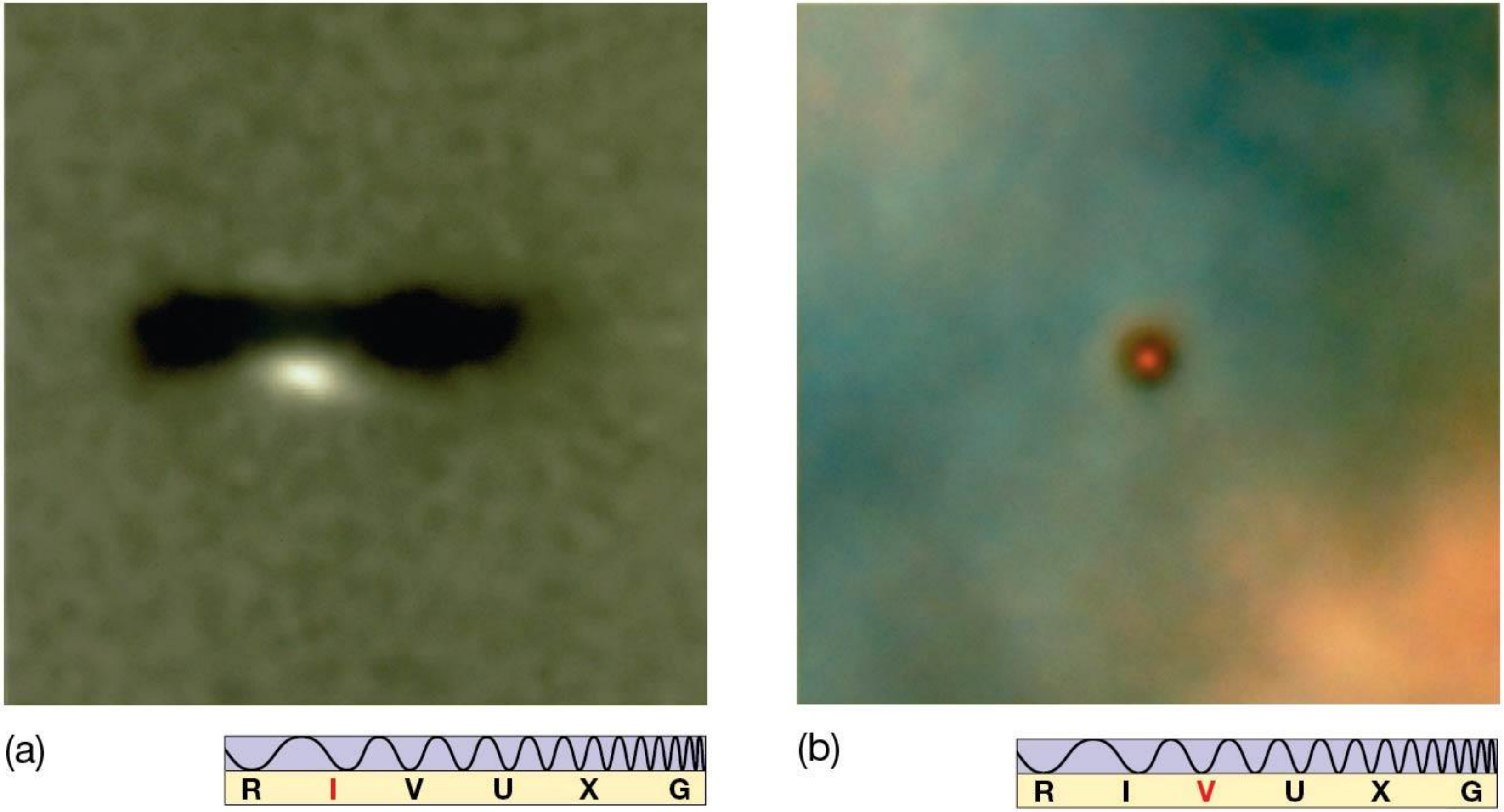
Evidence: Winds and Jets

- Winds and jets being emitted by Protostars.



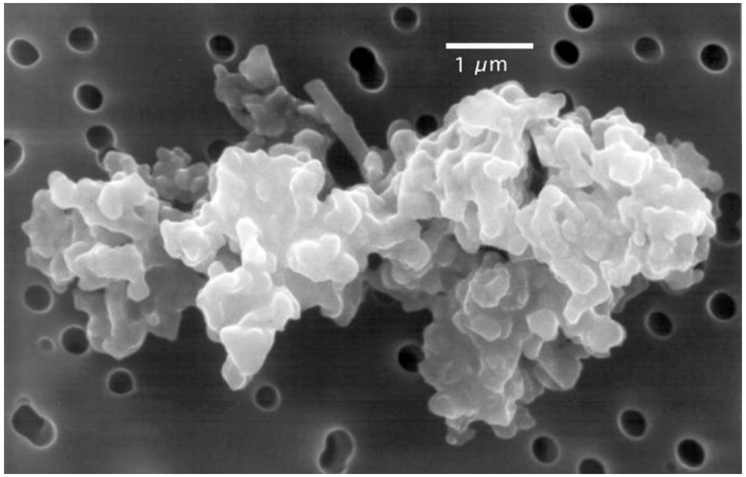
Evidence: Winds and Jets

- These Protostars are in Orion.



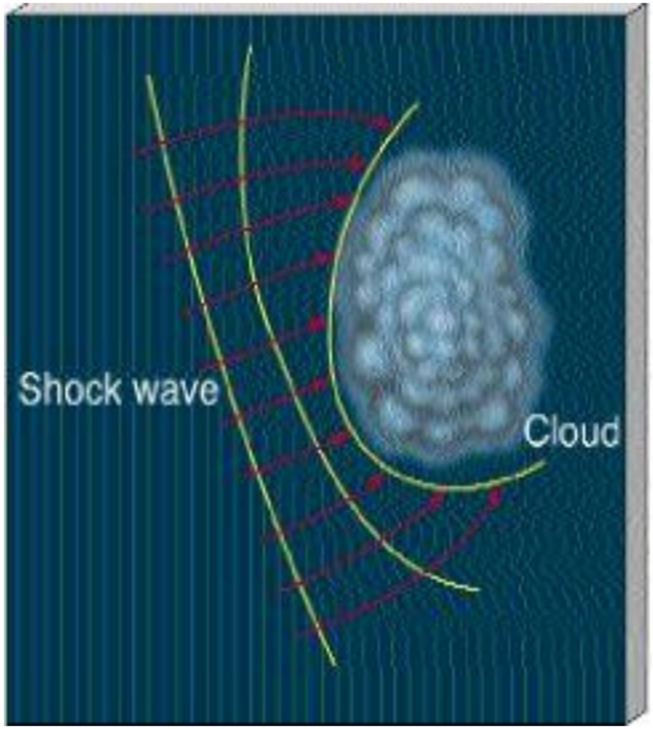
Condensation Theory

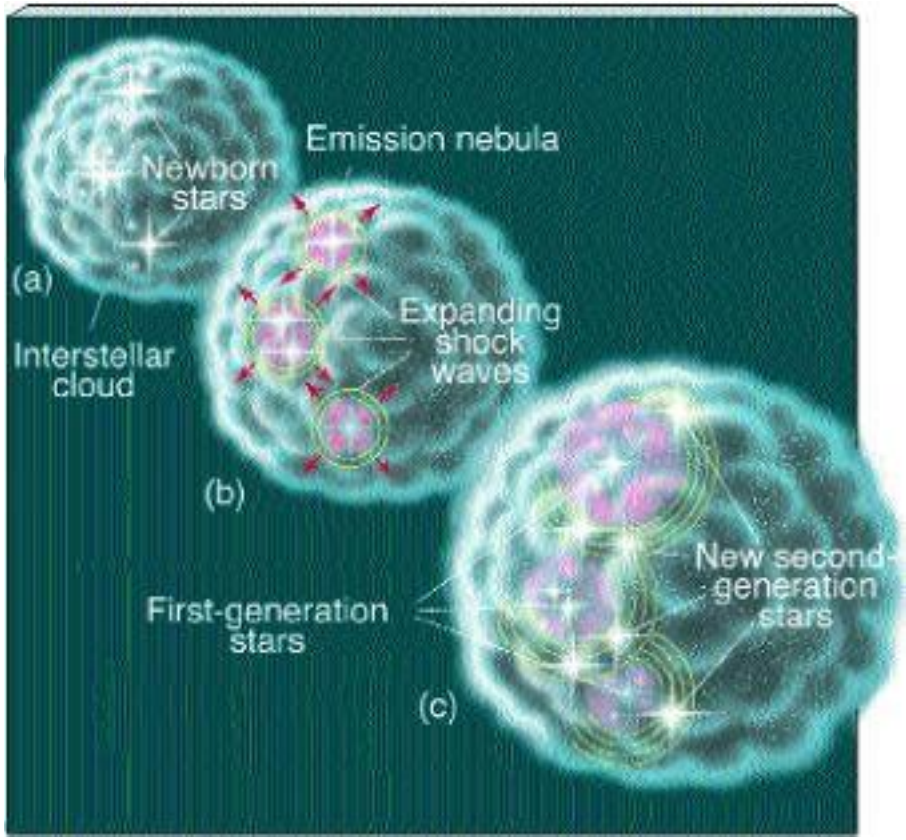
- The largest dust grains can act as condensation nuclei for accretion and grow larger. Examples include
  - Snowball in a snowstorm keeps growing larger as it collects snow.
  - Dust and soot in the atmosphere serve as condensation nuclei around which molecules of water vapor collect to form raindrops.



Shock Wave Theory

- Many Astronomers think that shock waves passing through the ISM can trigger star formation by compressing interstellar clouds and initiating the collapse process;





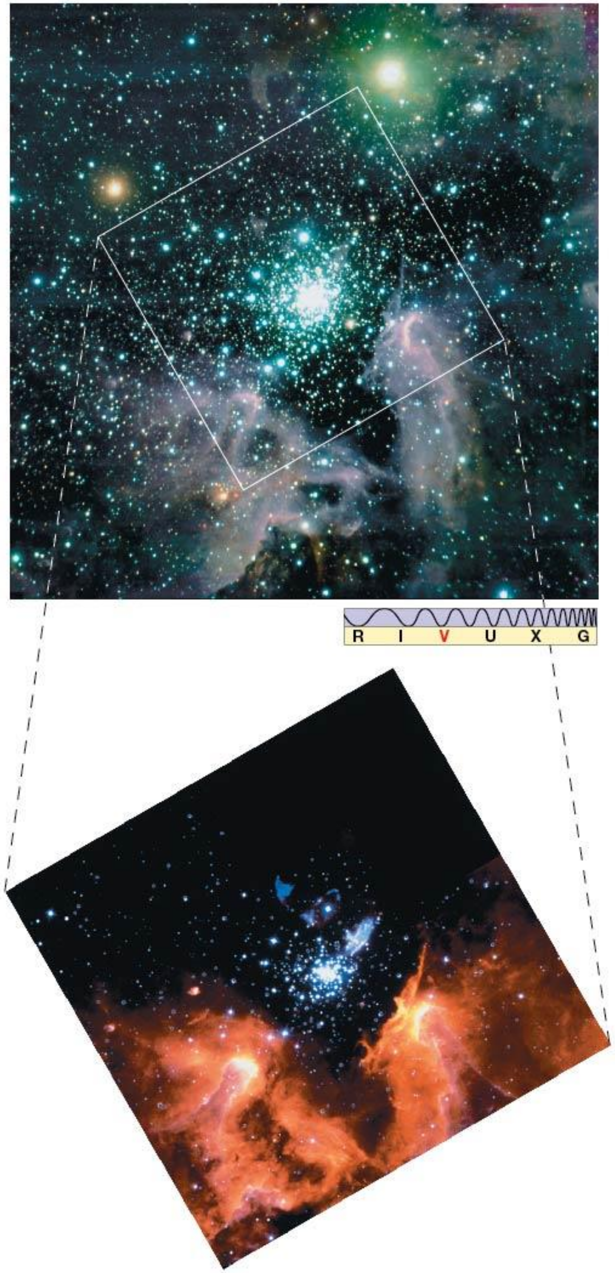
Shock Wave Theory

- Shock waves in the ISM are generated by:
  - The death of a nearby star, the size of or larger than the Sun
  - A nearby supernova explosion
  - Density waves in galactic spiral arms
  - Galactic Collisions

  - **The early universe was more or less free of dust, so shock waves in the early universe were probably the drivers of star formation.**

Star Clusters

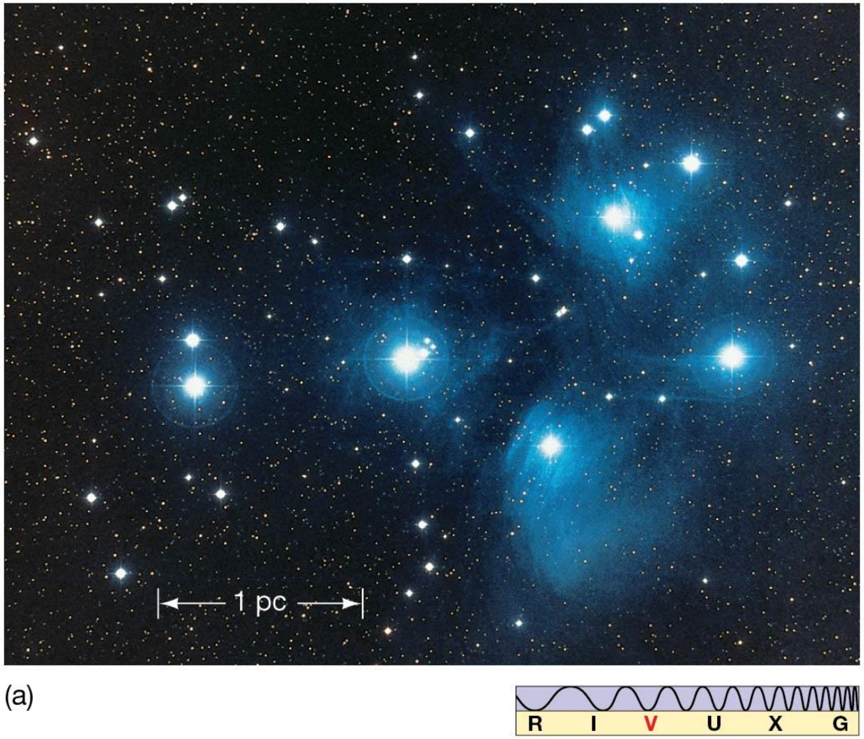
- Because a single interstellar cloud can produce many stars of the same age and composition, star clusters are an excellent way to study the effect of mass on stellar evolution.
- They come in two types:
  - **Open Clusters** are loosely bound and irregular. Less massive, more extended clusters are called **Associations.**
  - **Globular Clusters** are roughly spherical, made of older stars and found away from the plane of the Milky Way. They contain millions of stars over roughly 50 pc.



- One can roughly estimate the age of a star cluster by the H-R diagram of the stars in the cluster.
- If there are a significant number of large mass stars still populating the main sequence then the cluster must be young (because large mass stars stay only a short time on the main sequence).
- If there are fewer large mass stars but more small mass stars populating the main sequence then the cluster must be old (because small mass stars take a long time to get to the main sequence).
- One can estimate the age by noting where the population of stars begins to sharply diminish on the main sequence.

Star Clusters

- This is a young open star cluster called the Pleiades (136 pc away). The H–R diagram of its stars is on the right. This is an example of an open cluster.



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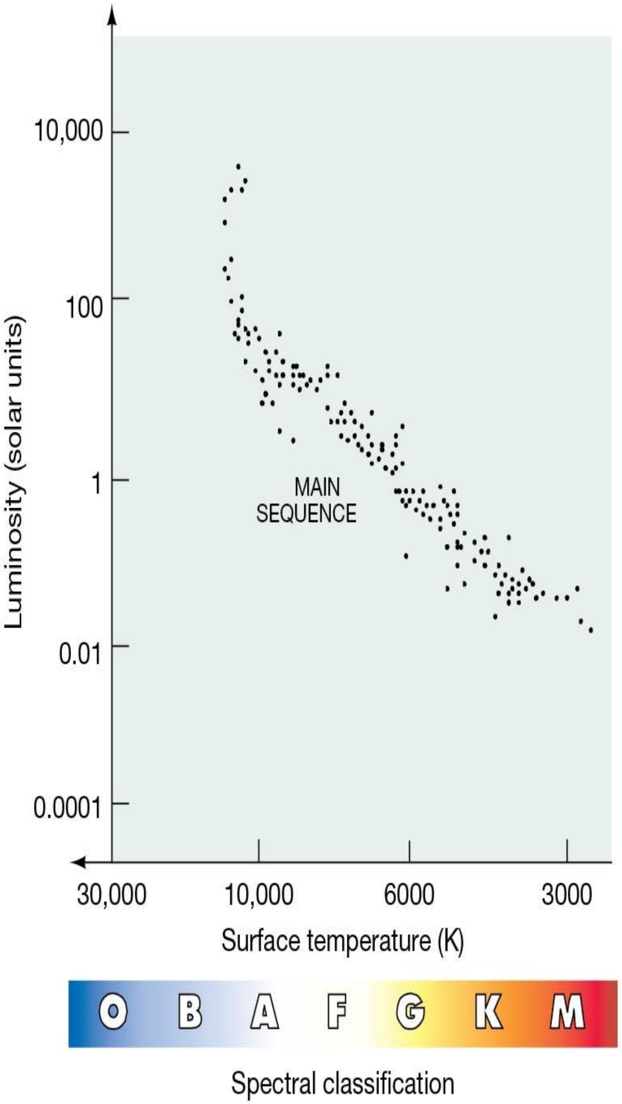

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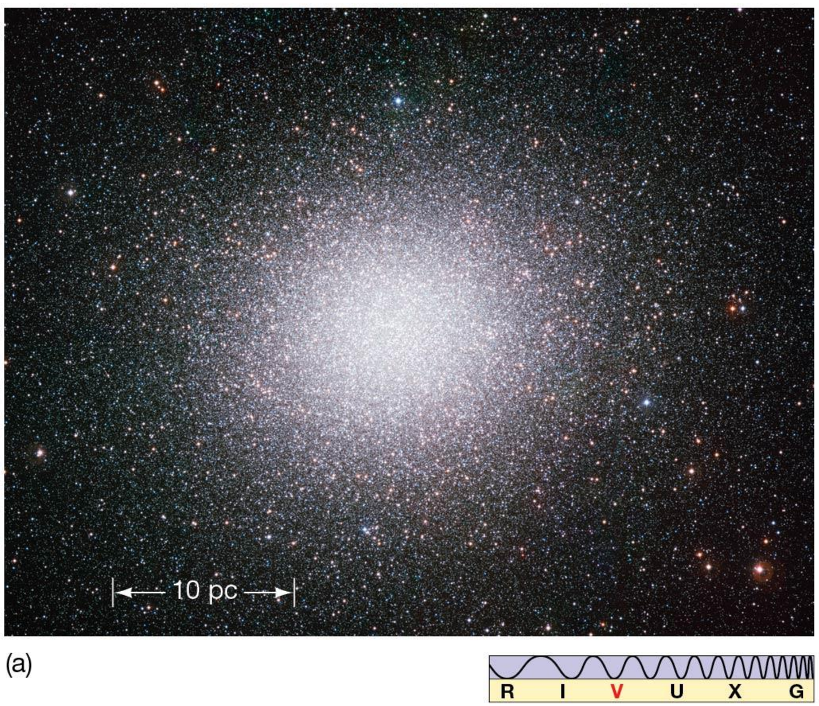
Star Clusters

- This is a globular cluster—note the absence of massive main-sequence stars and the heavily populated red giant region (about 1000 pc).



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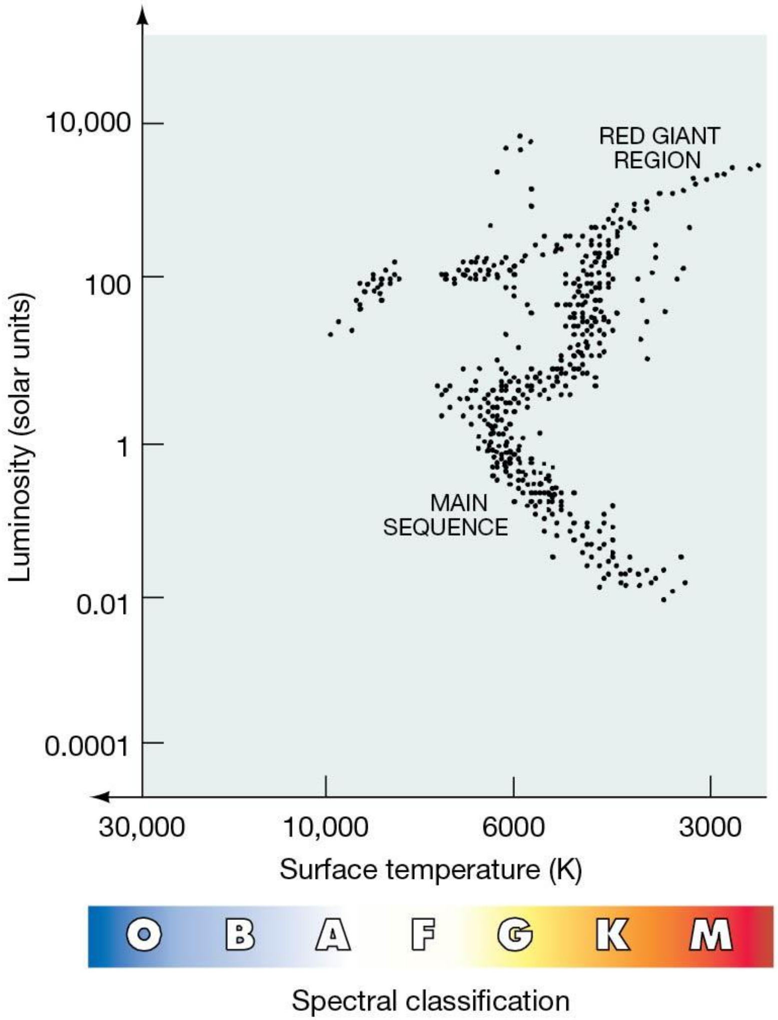

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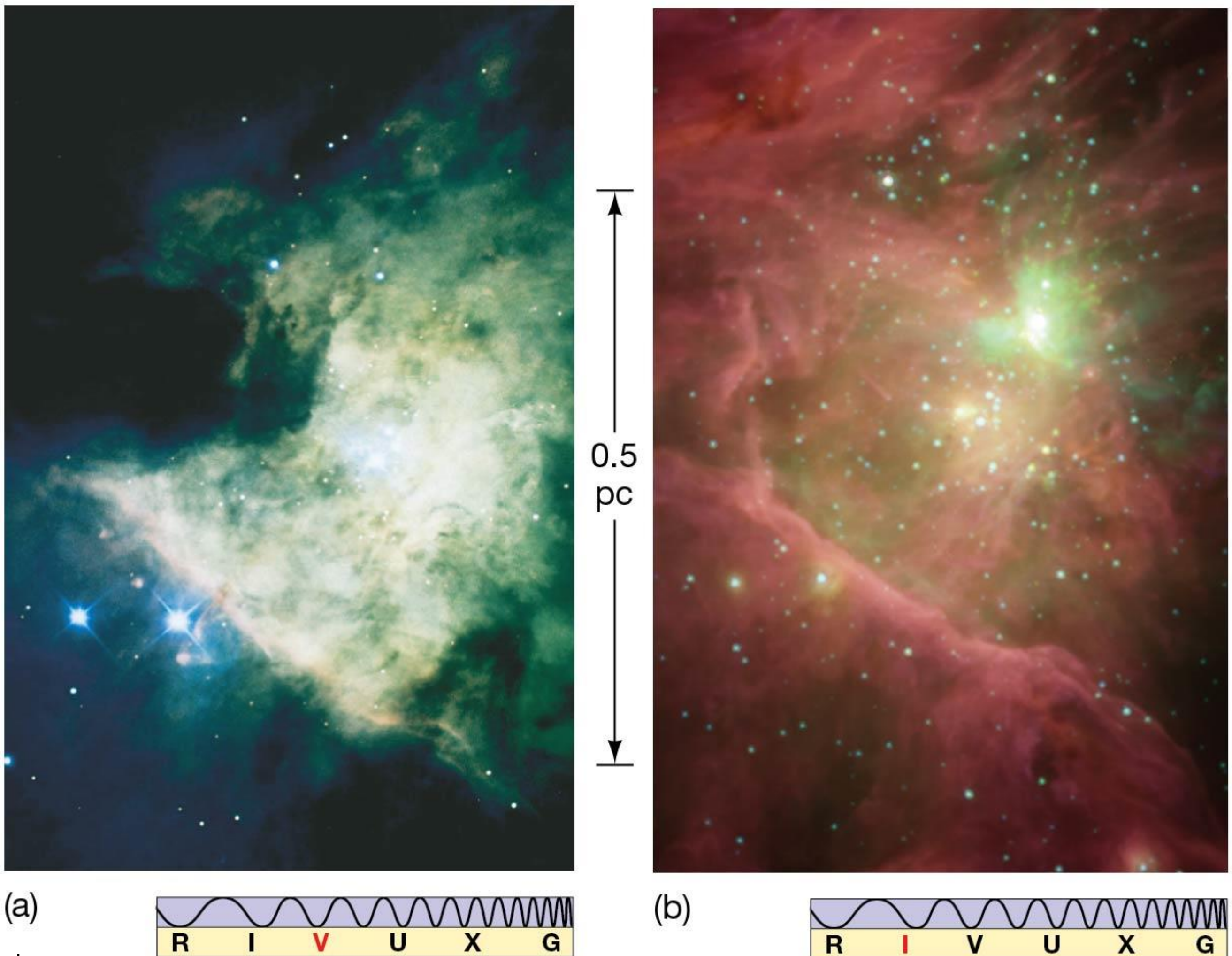
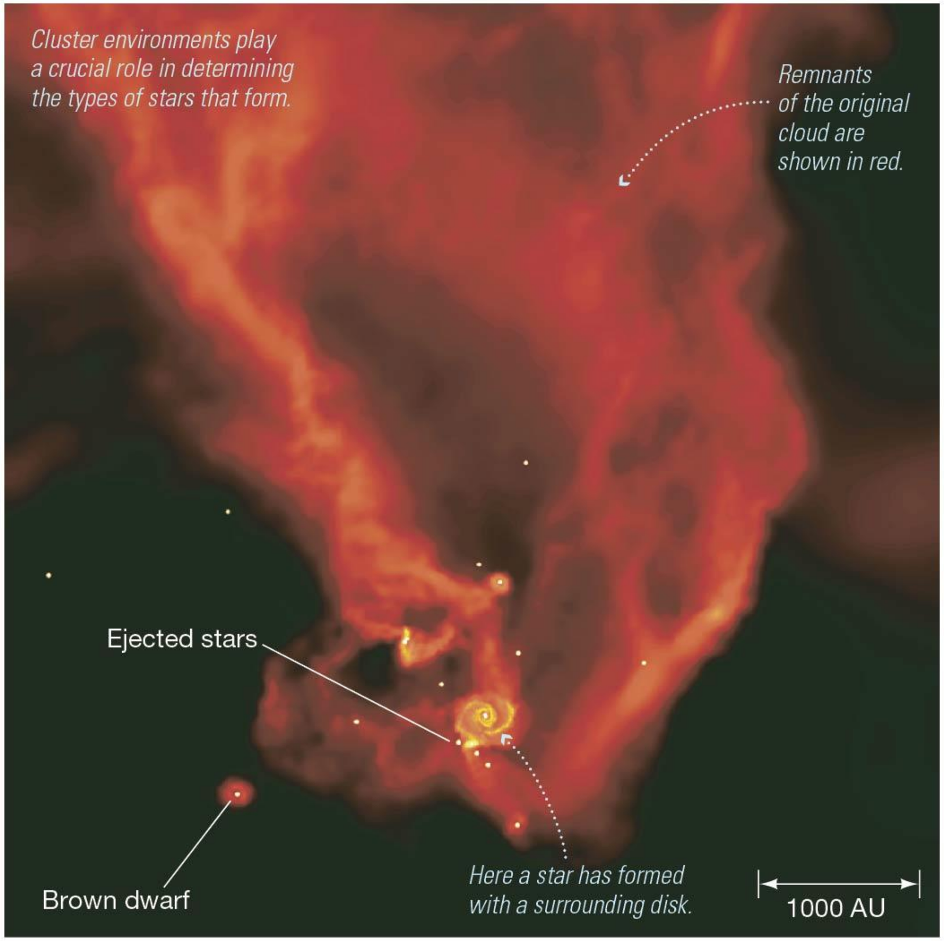
Star Clusters

- These images are believed to show a star cluster in the process of formation within the Orion Nebula.



Star Clusters

- Interactions between stars in a cluster can play an important role in determining its properties.
- O and B stars can blow away dust and gas before it has time to collapse, terminating the development of smaller Protostars.
- In dense clusters, interactions may cause mergers of protostars.
- This is a simulation of such a cluster.



Summary

- Star formation begins with fragmenting, collapsing clouds of dust and gas.
- The cloud fragment collapses due to its own gravity, and its temperature and luminosity increase. When the core is sufficiently hot, fusion begins.
- Collapsing cloud fragments and Protostars have been observed. Star formation has been observed near emission nebulae
- Mass determines where a star ends up on the main sequence.

Summary

- There is the question of what starts the collapse process.
- ISM shock waves may be one cause.
- One cloud typically forms many stars, as a star cluster.
- There are two types of clusters: Open Clusters and Globular Clusters.
- Very large, low mass open clusters are called Associations.
- Globular Clusters are old, very large and spherical. They lie outside the galactic plane.