The Birth of Stars

Stellar Evolution

The **lifetime of a star** is mainly determined by how long fusion reactions can be sustained in its core.

Studying the **evolution of stars** is complicated by the fact that the lifetime of a star ranges from a few million to a few billion years.

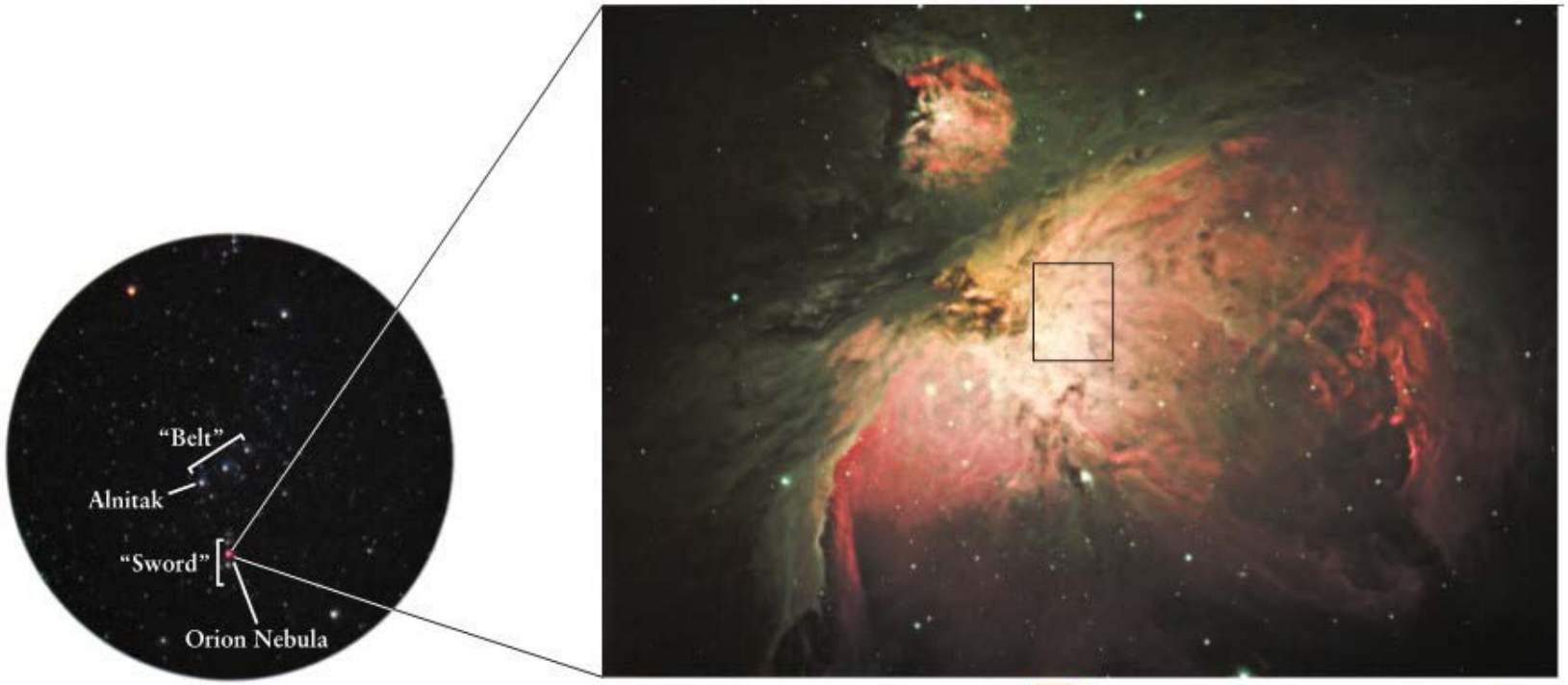
So how do we figure out how a star evolves?

1) **By studying a very large sample of stars** we can observe them going through different stages of their evolution.

2) **By creating sophisticated models of stellar evolution** and comparing them to observations of large samples of stars.

Interstellar Medium

The space between stars in a galaxy is not empty but is filled with gas and dust. This collection of gas and dust between stars in called **interstellar medium**. A **nebula** is just a **cloud** of interstellar gas and dust.



(a) A wide-angle view of Orion

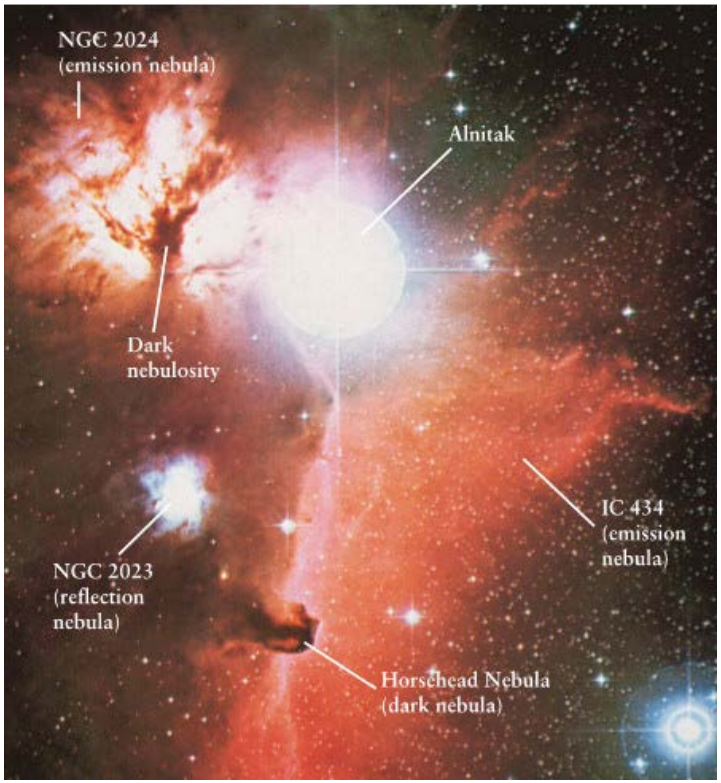
(b) A closeup of the Orion Nebula R I V U X G

Emission Nebulae: HII Regions

An **emission nebula** is one that contains strong emission lines.

The total mass in an emission nebula ranges from 100-10,000 $M_\odot$ scattered over a few light years. The gas in an emission nebula has a density ~ 1,000 H atoms cm^{-3}.

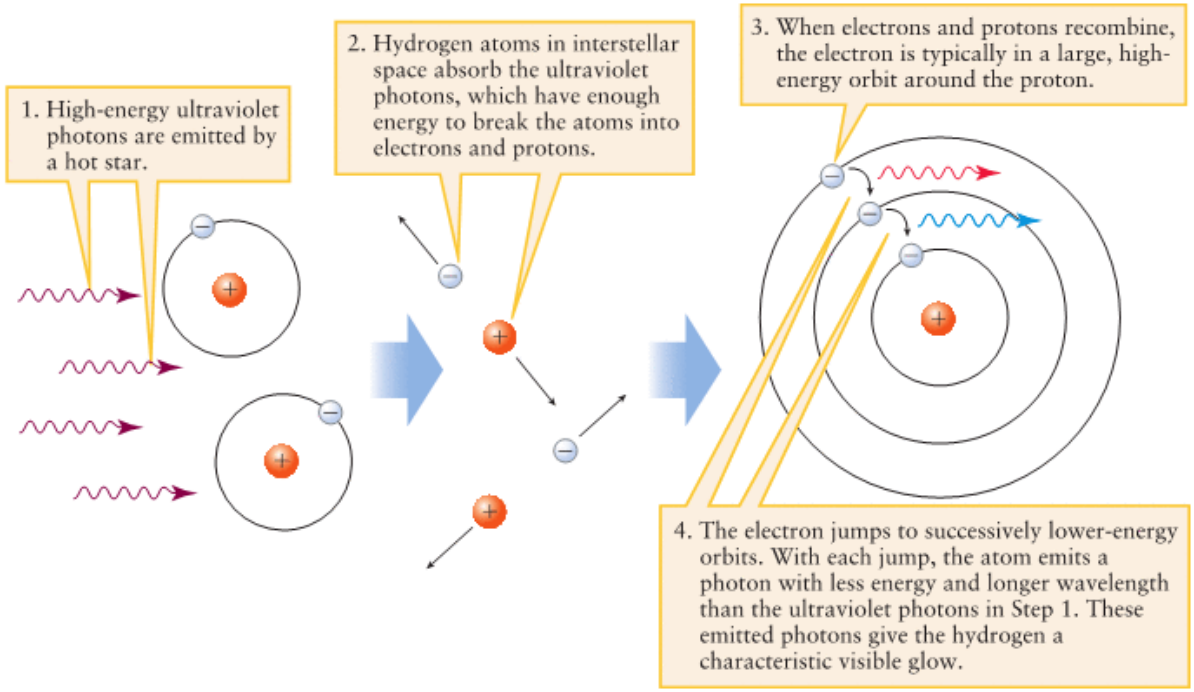
Emission nebulae are found near hot O and B stars. Such stars emit copious amounts of UV that can easily ionize H atoms. Emission nebulae (**HII regions**) are composed primarily of ionized hydrogen (HII).



Emission, reflection and dark nebulae in Orion.

Emission Nebulae: HII Regions

UV photons can easily ionize Hydrogen. **H II regions** are clouds of glowing low density gas and plasma that contain a large amount of ionized H. Free electrons can recombine with protons and usually get captured in a high energy level. As the **electron cascades** downward through the atom's energy levels toward the ground state, the atom emits photons with lower energy and longer wavelength than the photons that originally caused the ionization.



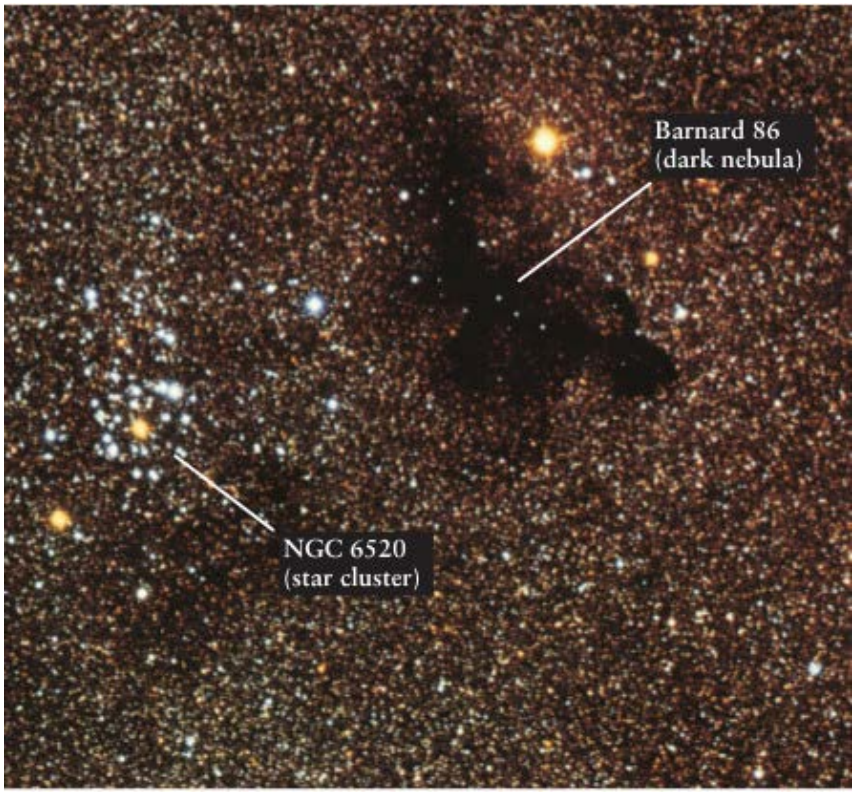
Dark Nebulae

In addition to gas the interstellar medium contains **dust grains**.

Dust grains are microscopic bits of solid matter found in interplanetary or interstellar space.

Dark nebulae are so opaque because of the large amount of dust grains that they **block any visible light** coming from stars that lie behind it.

Dark nebulae have typical temperatures of 10K-100K and densities of 10^4-10^9 particles per cm^3.



Dark nebulae have a relatively dense concentration of microscopic dust grains, which scatter and absorb light much more efficiently than single atoms.

Dark Nebulae

The **Horsehead Nebula** is a dark nebula in the constellation Orion.

The red glow originates from hydrogen gas predominantly behind the nebula, ionized by the nearby bright star Sigma Orionis.

Reflection Nebulae

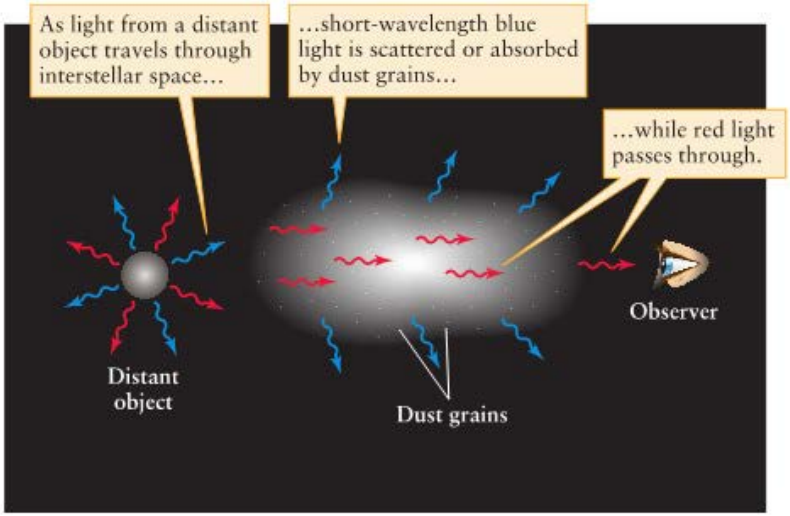
Reflection nebulae are clouds of dust that that do not emit their own light, but reflect and scatter the light of nearby stars.

Fine dust in the **Witch Head Nebula** nebula reflects the light from Rigel.

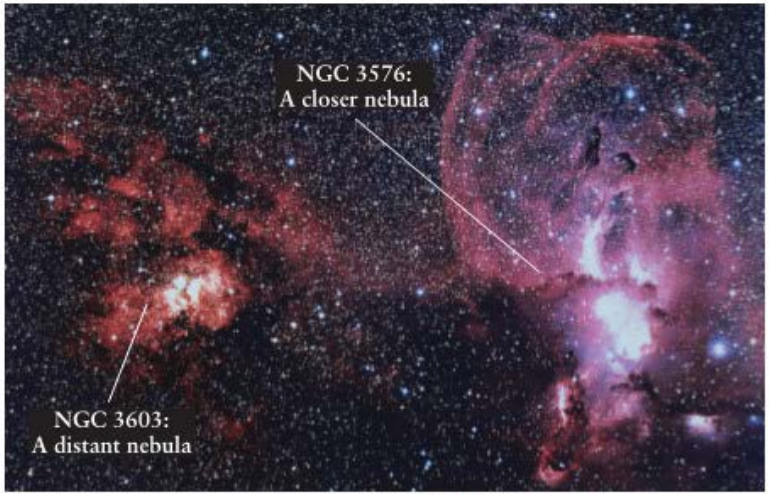
The blue color is caused not only by Rigel's blue color but because the **dust grains reflect blue light more efficiently than red.**

The **Witch Head Nebula** glows primarily by light reflected from Rigel, located just outside the top right corner of the image.

Interstellar Extinction and Reddening



(a) How dust causes interstellar reddening



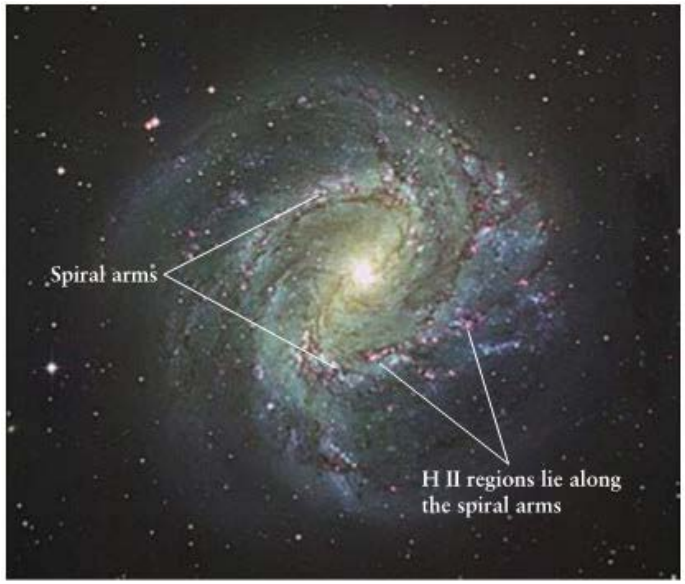
(b) Reddening depends on distance R I V U X G

Interstellar extinction is the dimming of light as it passes through the interstellar medium.

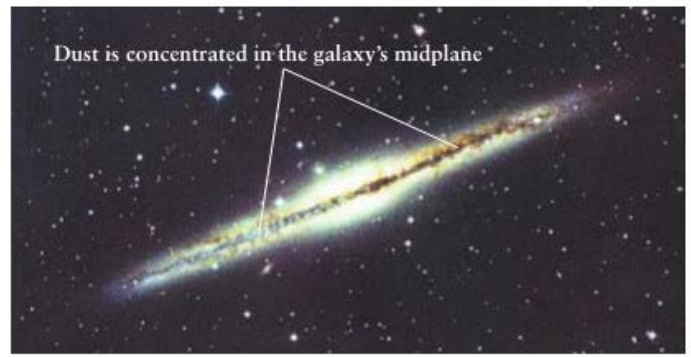
If you look at a source through a cloud of dust grains more blue than red light will be scattered out of your line of sight. Such sources as said to be **reddened**.

Explain: Red Nebula (why red?), **Blue Nebula** (why blue?) Dark Nebula (why dark?), Sky (why blue?), Sun during sunset (why red?)

Location of Interstellar Gas and Dust



(a) We see spiral galaxy M83 nearly face-on



(b) We see spiral galaxy NGC 891 nearly edge-on

Observations indicate that bright stars, gas, and glowing nebulae are mostly located near the mid-planes of spiral galaxies, and that they are concentrated along arching spiral arms that wind outward from the centers of the galaxies.

The spiral arms are the locations of most of the star formation.

Interstellar Gas and Dust in the Milky Way

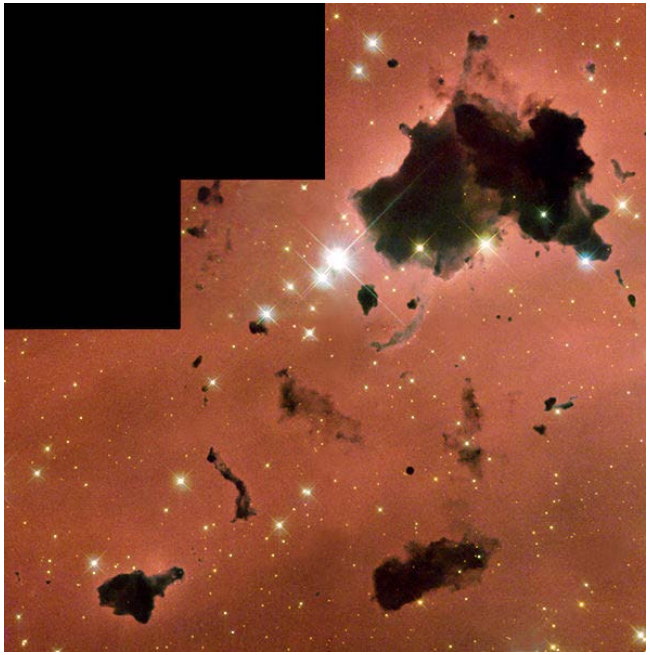
Birth of Stars: Bok Globules

For interstellar material to condense gravity must overcome the pressure that is pushing the material apart.

Regions with high density and low temperature gas are places where gravity may overcome the gas pressure resulting in the collapse of the gas.

Dark nebulae are regions of low temperature and relatively high density of gas and dust and therefore suitable locations for stars to form.

A **Bok globule** is a dark cloud of dense dust and gas in which star formation sometimes takes place. They are found within H II regions, and typically have a mass of about 2 to 50 $M_\odot$ contained within a relatively small region of ~ 1 pc across.



Bok globules in the H II region IC 2944. They contain molecular hydrogen, helium, carbon oxides, and around 1% (by mass) of silicate dust.

Birth of Stars: Protostars

Any sufficiently large disturbance to the cloud may upset its state of equilibrium and lead to its collapse. Examples of disturbances are shock waves from supernovae; spiral density waves within galaxies and the close approach or collision of another cloud.

British astronomer **Sir James Jeans** derived a formula for calculating the mass and size that a cloud would have to reach as a function of its density and temperature before gravitational contraction would begin. This critical mass is known as the Jeans mass. It is given by the following formula:

$M_j = \frac{9}{4} \times \left(\frac{1}{2\pi n}\right)^{\frac{1}{2}} \times \frac{1}{m^2} \times \left(\frac{kT}{G}\right)^{\frac{3}{2}}$, n is the density, m is the mass of the average particle and T is the gas temperature, k $= 1.38 \times 10^{-23}$ J/K, G $= 6.67 \times 10^{-11}$ N m^2/kg

Birth of Stars: Protostars

The initial gravitational collapse of gas and dust into clumps called **protostars** is thought to occur in dark nebulae where temperatures are relatively low and densities are relatively high (e.g., Bok globules or Barnard objects).

Models of protostars indicate that as they collapse **gravitational energy is converted to thermal energy**. This is called Kelvin-Helmholtz contraction.

Energy is initially transported outward by convection, heating the surface.

Protostars initially have relatively large luminosities compared to stars of similar temperature because they start off with very large radii.

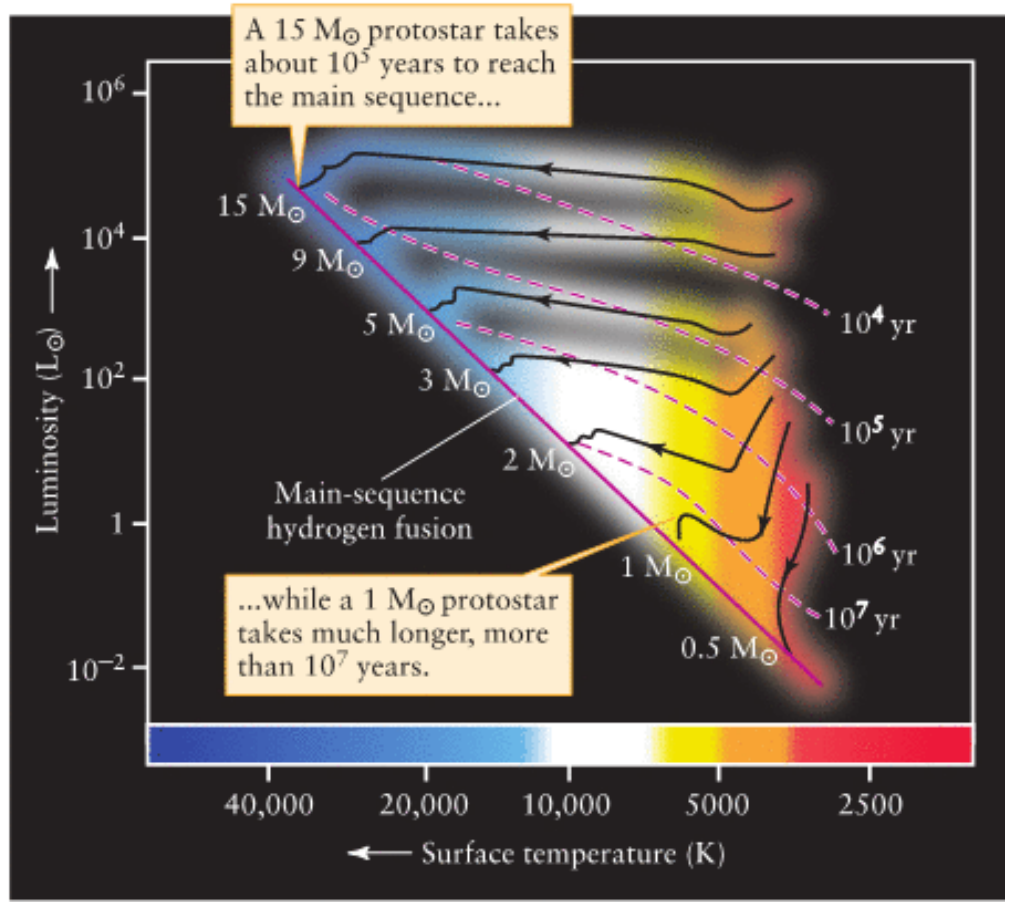
Remember
$L = 4\pi R^2 F = 4\pi R^2 \sigma T^4$

Birth of Stars: Protostars

Models of protostars predict the evolution of their luminosity and temperature as they contract.

The evolution and time it takes a protostar to reach the main sequence branch depends significantly on its mass.

How long does it take a $10M_\odot$, $5M_\odot$ and $2M_\odot$ protostar to reach the main sequence.



Pre-Main-Sequence Evolutionary Tracks.

Energy Transport of Protostars

The evolution and energy transport of protostars depends significantly on their mass.

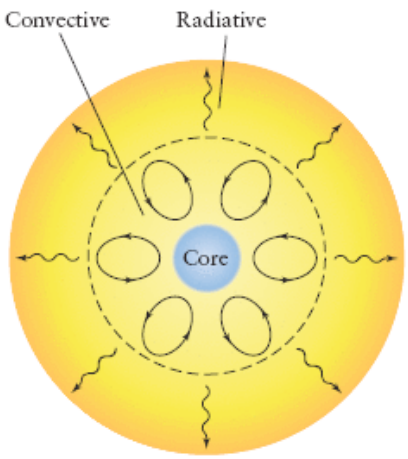
Case 1:0.4 $M_\odot$ < $M_{protostar}$ < 4 $M_\odot$
Energy initially is transported out via convection. A ~1 $M_\odot$ protostar is **initially too opaque** for radiation to be transported out from its center and energy is more efficiently transported via convection. The surface temperature remains almost constant during contraction and the luminosity decreases since the radius decreases ($L = 4\pi R^2 \sigma T^4$).

After a time, the interior becomes ionized, which makes it less opaque. Energy is then conveyed outward by radiation in the interior and by convection in the opaque outer layers, just as in the present-day Sun.

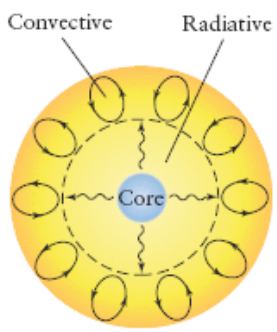
Energy Transport of Protostars

Case 2: $M_{protostar} > 4\ M_{\odot}$
A massive protostar contracts and heats more rapidly and the surface temperature increases as the protostar collapses. They have convective interiors but radiative outer layers.

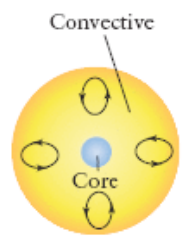
Case 3: $M_{protostar} < 0.4\ M_{\odot}$
The interior temperature is never high enough to fully ionize the interior. The interior remains too opaque for radiation to flow efficiently, so energy is transported by convection.



(a) Mass more than about 4 $M_{\odot}$: Energy flows by convection in the inner regions and by radiation in the outer regions.



(b) Mass between about 4 $M_{\odot}$ and 0.4 $M_{\odot}$: Energy flows by radiation in the inner regions and by convection in the outer regions.

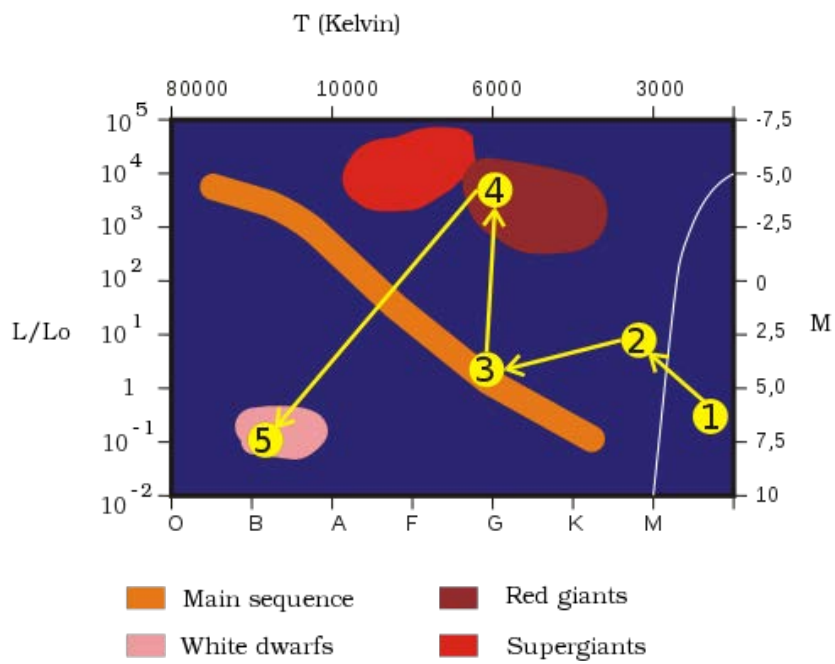


(c) Mass less than 0.4 $M_{\odot}$: Energy flows by convection throughout the star's interior.

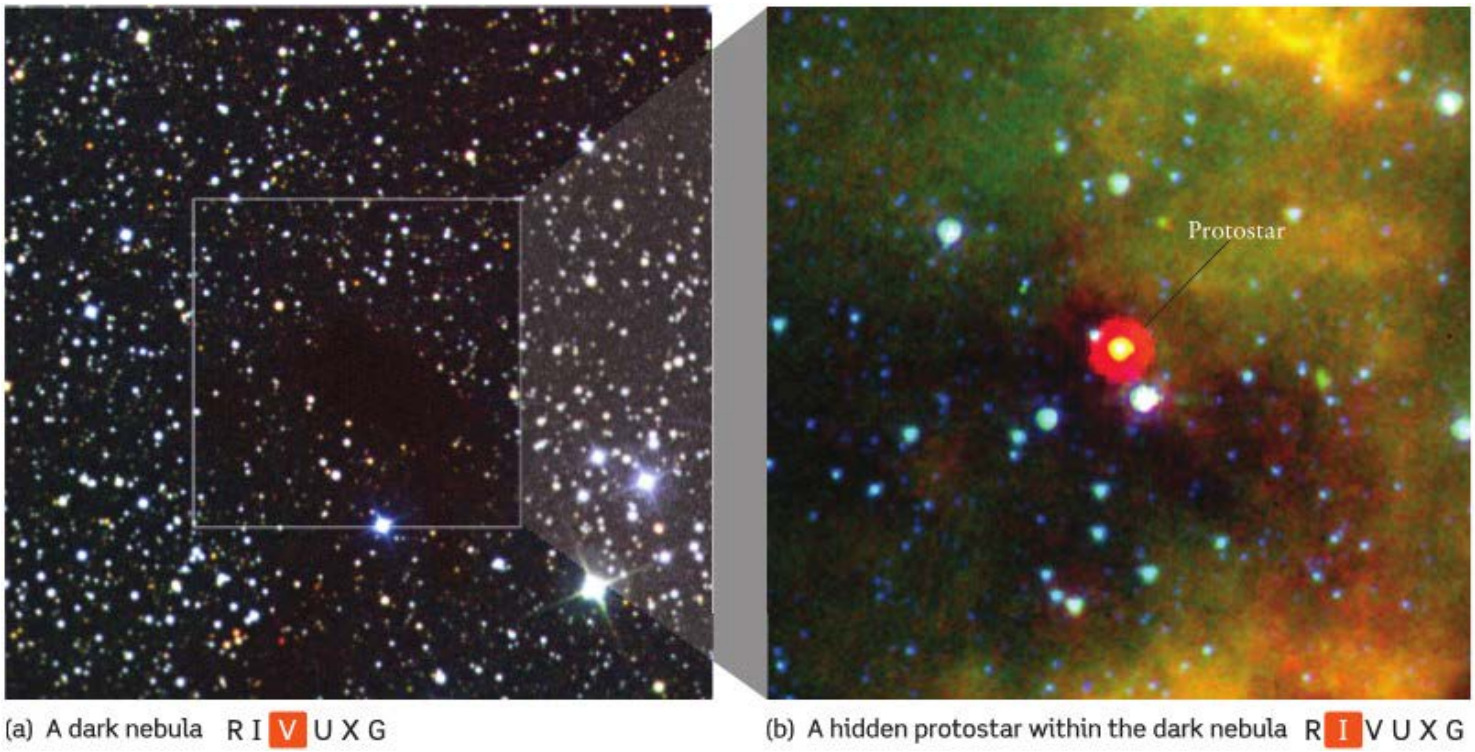
Evolution of Protostars

The point along the main sequence where each evolutionary track ends depends on the star's mass. The most massive stars are the most luminous and their evolutionary tracks end at the upper left of the main sequence, while the least massive stars are the least luminous and their evolutionary tracks end at the lower right of the main sequence.

Simplified illustration of the evolution of a star.



How to find a Protostar

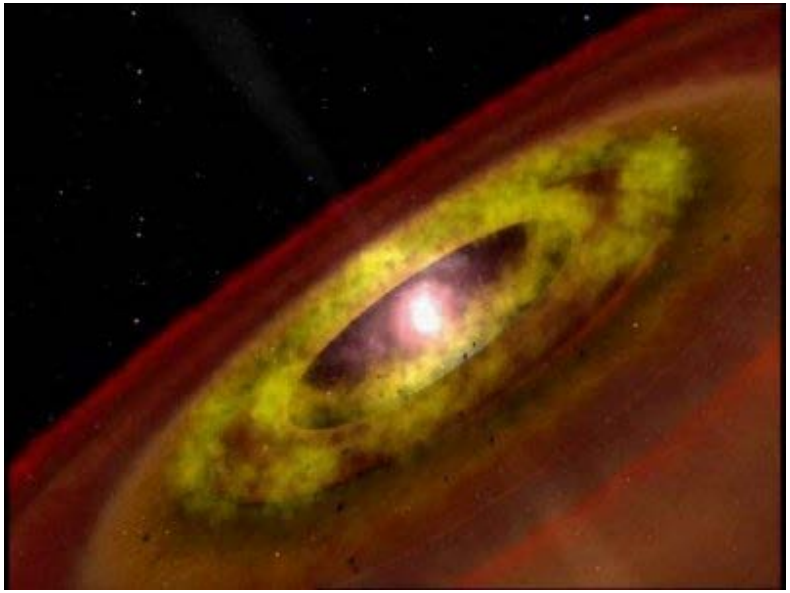


Protostars are surrounded by dense gas and dust that absorbs most visible light. The part of the nebular surrounding a protostar is often called the **cocoon nebula**.

The cocoon nebula absorbs visible light from the protostar raising its temperature to a few hundred kelvins. The cocoon emits in the IR that can be observed.

Outflows from Protostars

T - Tauri stars are variable pre-main sequence stars (< 3 $\mathbf{M_\odot}$) found near molecular clouds and identified by their optical variability and strong emission and absorption lines.

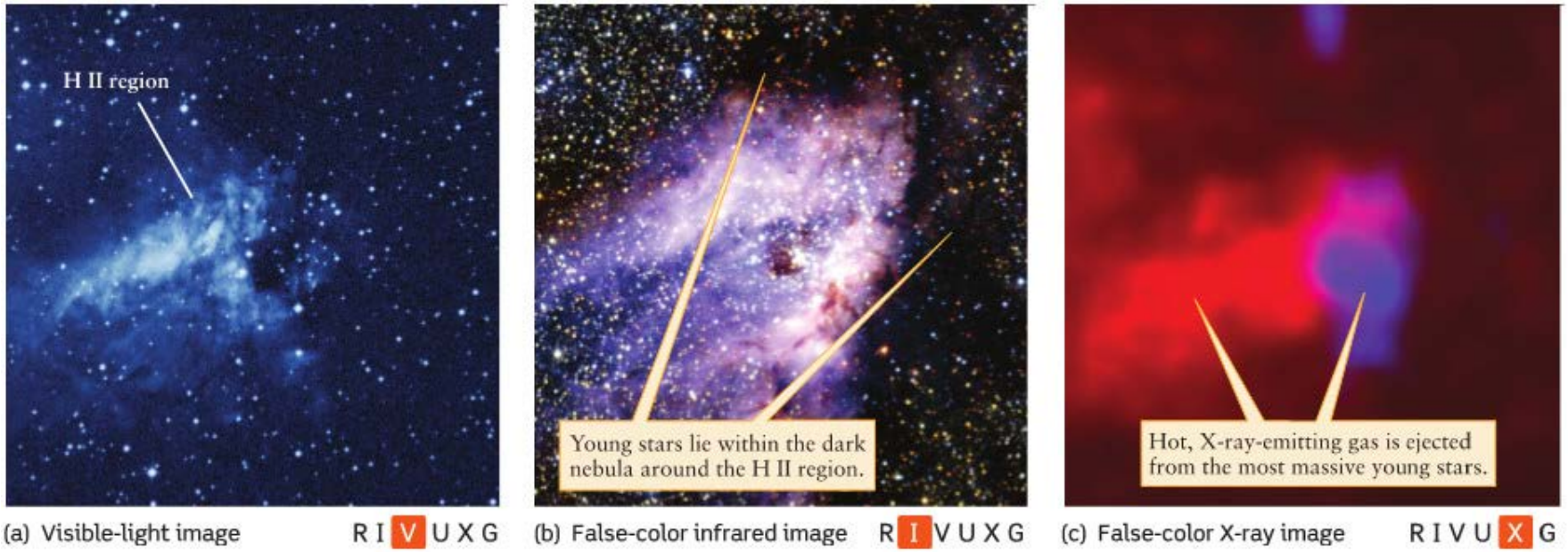


The Doppler shifts of these emission lines suggest that these protostars **eject gas** at speeds around 80 km/s. They eject about 10^{-7} $\mathbf{M_\odot}$ per year for about 10^7 years.

They typically rotate with a period between one and twelve days, and are very active and variable.

Outflows from Protostars

Massive pre-main sequence stars (>3 $\mathbf{M_\odot}$) do not vary significantly but have fast winds that are driven by radiation pressure.



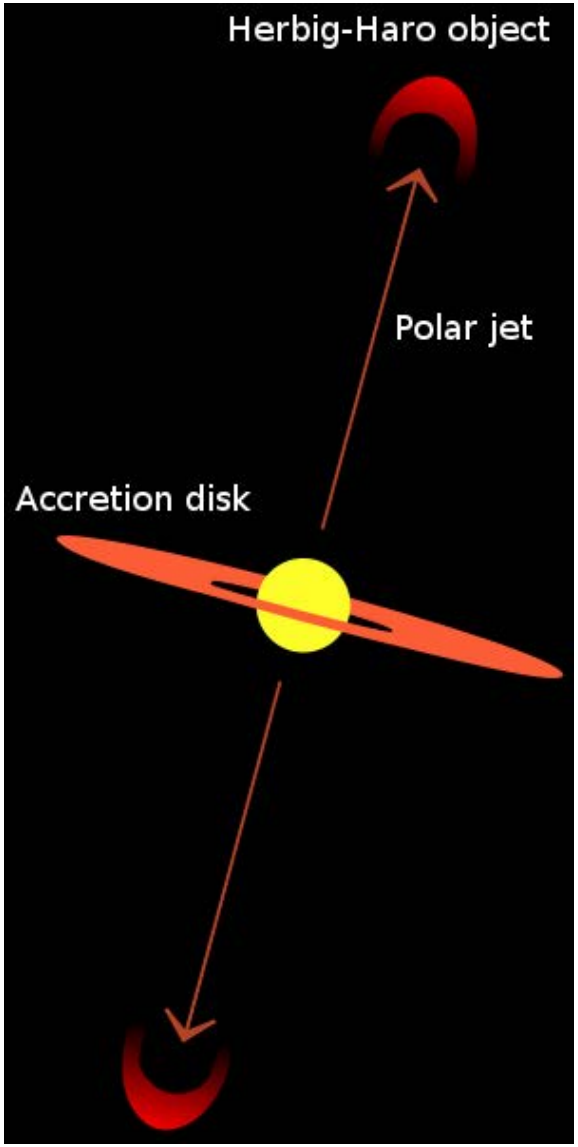
(a) The **Omega Nebula (HII region in the constellation Sagittarius)** in visible, (b) in Infrared and (c) in X-rays. The Infrared allows us to see through the dust and the detection of X-rays indicates that the massive stars in this star forming region are ejecting winds of gas with temperatures of up to 7×10^6 K.

Bipolar Outflows and Herbig-Haro Objects

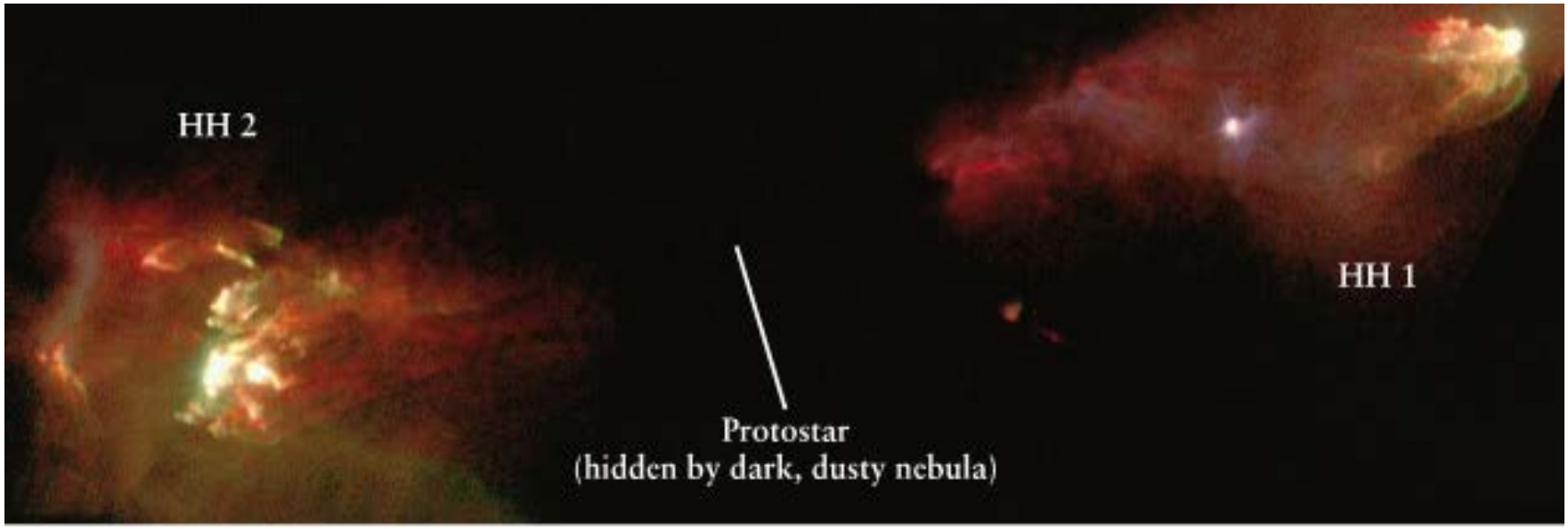
Many pre-main sequence stars eject material along **collimated narrow jets** pointed in opposite directions.

These **bipolar outflows** occasionally slam into gas in the interstellar median and produce knots of ionized hot gas.

These small glowing knots of gas are called **Herbig-Haro objects**.

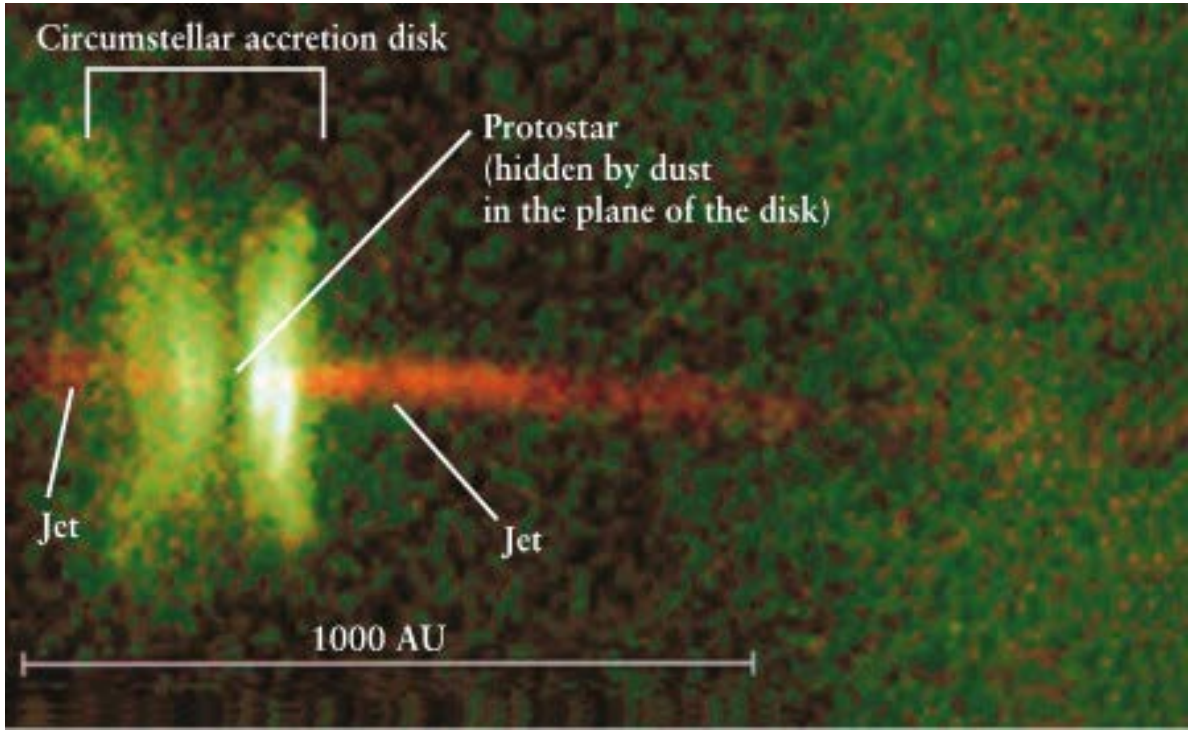


Bipolar Outflows and Herbig-Haro Objects



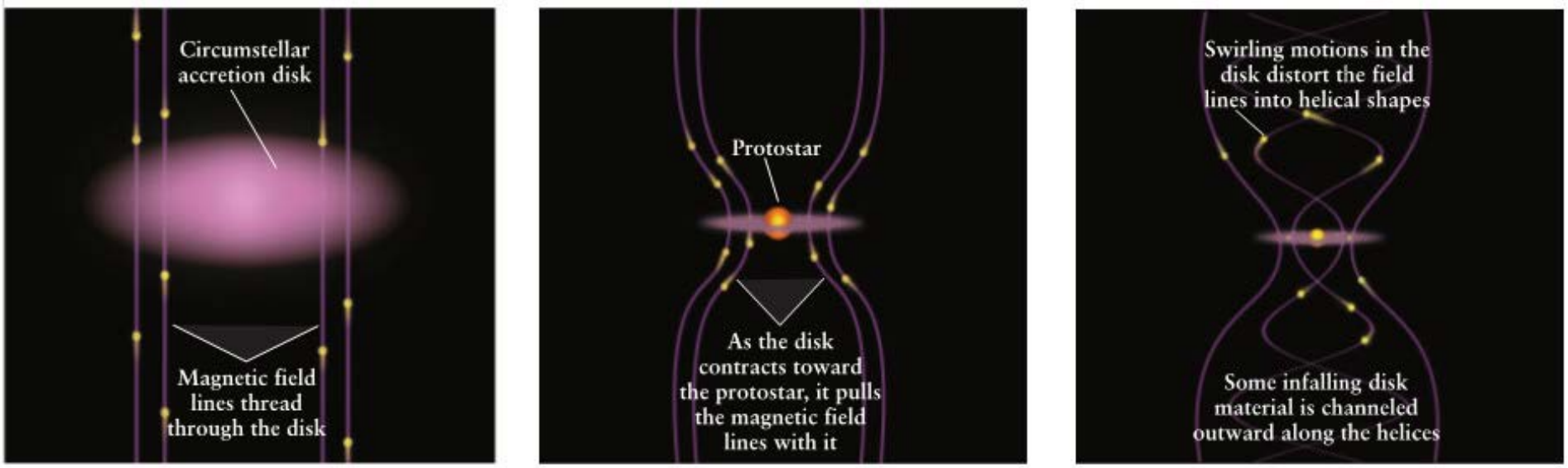
HST images of the Herbig-Haro knots HH1 and HH2 which are produced by the two jets from a single young star in the constellation Orion. These jets slam into the interstellar medium producing knots of ionized hot gas. The heated gas produces an emission spectrum. HH1 and HH2 are ~1.1 light-years apart.

Accretion on a Protostar



As the protostar collapses it spins faster and the **protostar nebula** flattens into a **circumstellar accretion disk**. We think that this type of flattening also occurred in the solar nebula which lead to the formation of the Sun and planets. Particles orbiting in the disk of the protostar collide and gradually loose momentum slowly drifting inward to add to the mass of the protostar at the center.

How Are Jets Formed?



(a) (b) (c)

Star Clusters

A dark nebula has about 10-1,000 $M_\odot$ of gas and dust enough to form many stars. These groups of stars are called **star clusters**.

An **open cluster** is a group of up to a few thousand stars that were formed from the same giant molecular cloud, and are still **loosely gravitationally bound** to each other. In contrast, **globular clusters** are **very tightly bound by gravity**.

Open clusters become **disrupted by close encounters** with other clusters and clouds of gas as they orbit the galactic center, as well as losing cluster members through internal close encounters.

Over time, radiation pressure from the cluster will disperse the molecular cloud. Typically, ~ **10% of the mass of a gas cloud will coalesce into stars** before radiation pressure drives the rest away.

Star Clusters

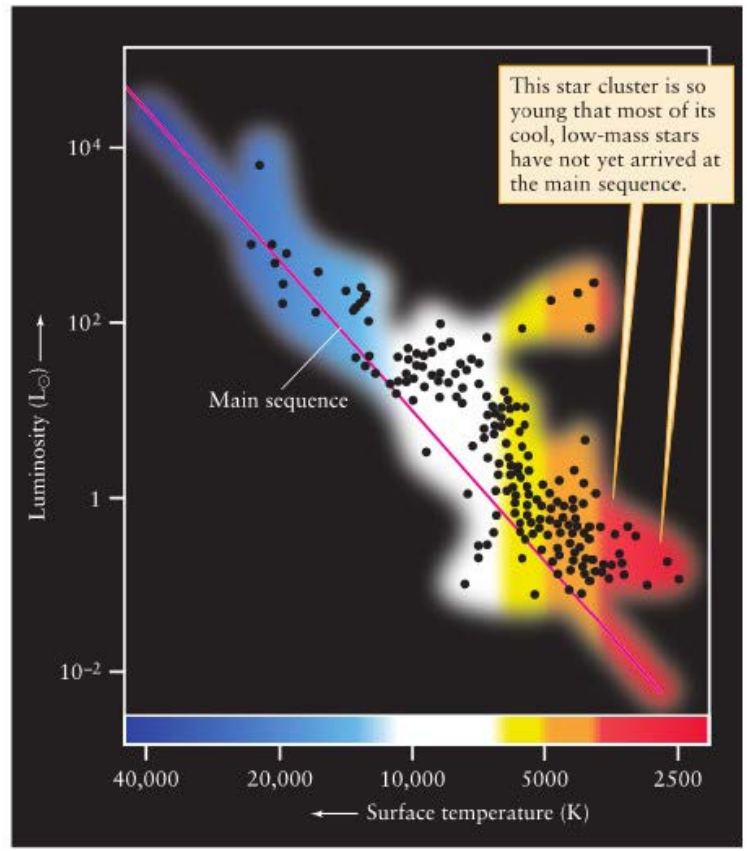
Because the stars in a star cluster were all born at roughly the same time, the different **properties of all the stars in a cluster are a function only of mass.** By studying stars clusters we see how stars of different mass evolve differently.

Massive protostars will end up first on the main sequence as O or B stars while **low mass protostars** may still be in the pre-main-sequence phase. The O and B stars will produce copious amounts of UV that will ionize gas in the dark nebular and form H II regions.

If a group of stars is gravitationally unbound from the very beginning then the group is called a **stellar association**. Because young stellar associations are typically dominated by luminous O and B main-sequence stars, they are also called **OB associations**.

Star Clusters

(a) The star cluster NGC 2264 R I V U X G

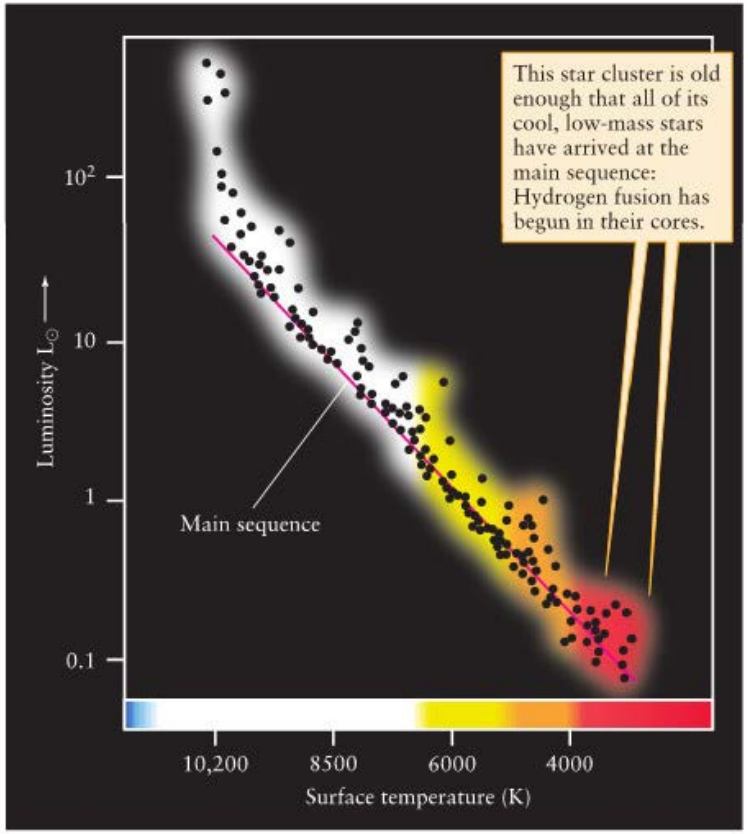


(b) An H-R diagram of the stars in NGC 2264

H II region and the young star cluster NGC 2264 in the constellation Monoceros. It lies ~ 2600 ly from Earth. (b) Each dot plotted on this H-R diagram represents a star in NGC 2264 whose luminosity and surface temperature have been determined. This star cluster probably started forming only 2 million years ago. Why is the nebular reddish?

Star Clusters

(a) The Pleiades star cluster R I V U X G



(b) An H-R diagram of the stars in the Pleiades

The Pleiades and its H-R Diagram (a) The Pleiades star cluster is 380 ly from Earth in the constellation Taurus, and can be seen with the naked eye. (b) Each dot plotted on this H-R diagram represents a star in the Pleiades whose luminosity and surface temperature have been measured. The Pleiades is ~5×10^7 years old. What expelled gas away from the stars? What is producing the blue light?

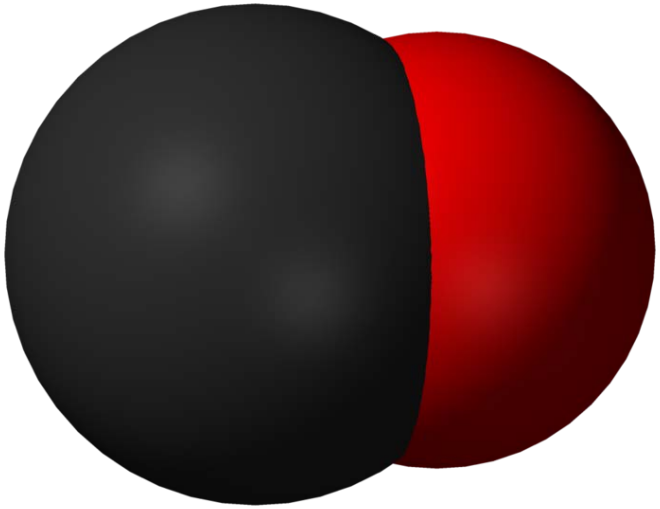
How to Find Dark Nebulae and Molecular Clouds

It's challenging to detect a **dark nebula**. Unless it's embedded in a larger bright region of stars or in an H II region it is **difficult to detect in the visible band.**

Dark Nebulae emit in the mm band and are usually detected at these wavelengths. **Millimeter wavelengths can also pass unaffected through interstellar dust.**

Molecules in dark nebulae can vibrate and rotate at only certain energy levels. When a molecule transitions between energy levels it emits a photon in the ~1-10 mm range.

What's the frequency at 3mm? What kind of telescope would you use to detect this?



CO Molecule

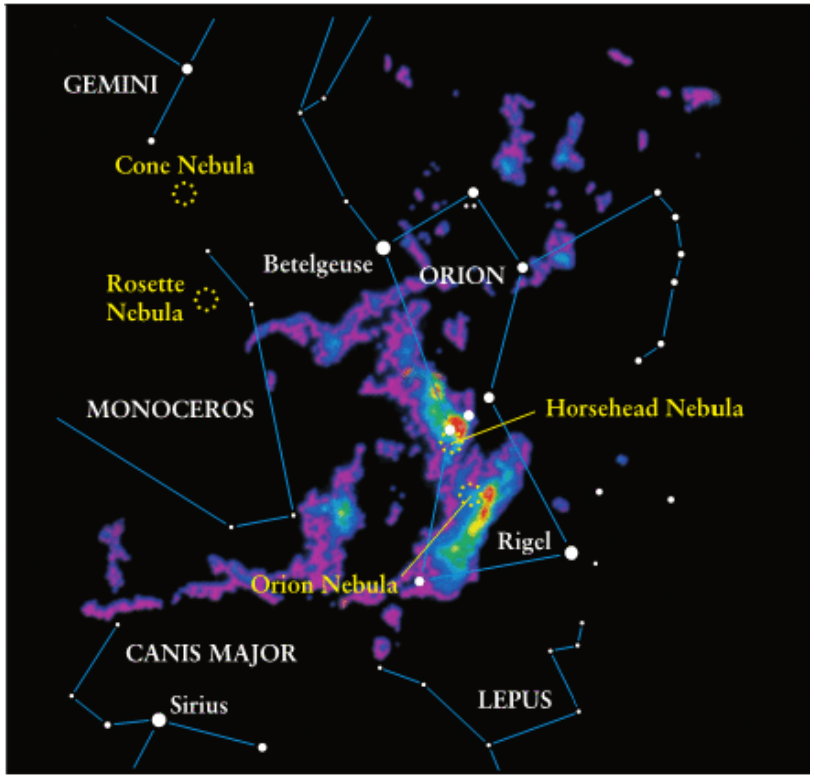
Emission from hydrogen molecules in the mm band is very weak (symmetric molecule) while mm emission from CO molecules is much stronger.

In interstellar space for every CO molecule there are about a 10,000 H_2 molecules so one can **use the CO as a tracer for H_2**.

How to Find Dark Nebulae and Molecular Clouds

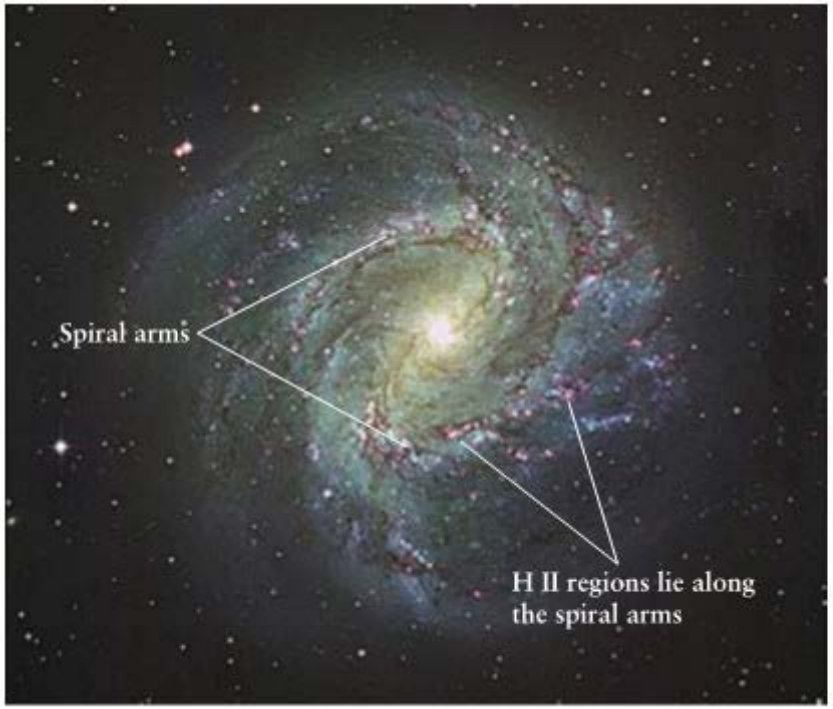
A radio telescope was tuned to a wavelength of 2.6 mm to detect **emissions from CO molecules in the constellations Orion and Monoceros.**

The map shows a 35° × 40° section of the sky. The Orion and Horsehead star-forming nebulae are located at sites of intense CO emission (shown in red and yellow), indicating the presence of a particularly dense molecular cloud at these sites of star formation.



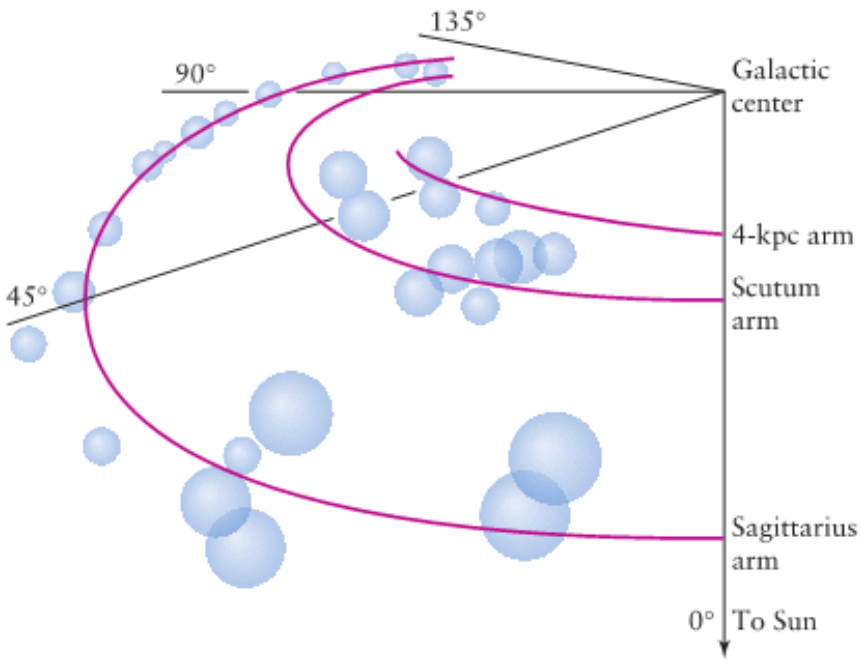
Map of CO Emission

Molecular Clouds and H II Regions in Spiral Arms



(a) We see spiral galaxy M83 nearly face-on

This face-on view of M83 shows luminous stars and H II regions along the spiral arms.



Molecular clouds in an inner part of our Galaxy as seen from a vantage point above the Sun. These clouds lie primarily along the Galaxy's spiral arms.

Triggered Star Formation by Spiral Arms and O and B Stars

A **giant molecular cloud** is **compressed** when it passes through a spiral arm. Once O and B stars are formed they emit copious amounts of UV that ionize the surrounding gas in the cloud producing H II regions.

Stellar winds from young O and B stars also produce a **shock wave** that compresses gas farther into the giant molecular cloud. This **triggers** star formation, producing more O and B stars, which stimulate still more star formation, and so on.

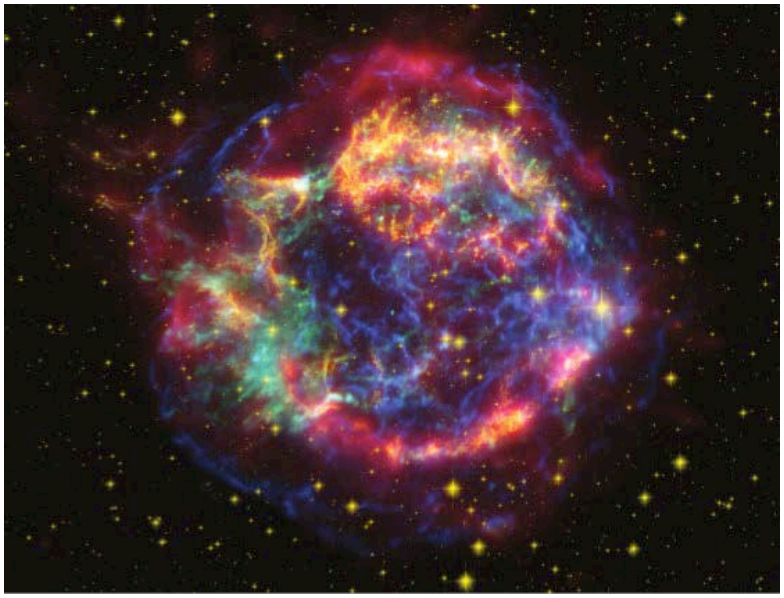
Radiation and winds from the hot, young O and B stars at the center of this Spitzer image of RCW 79 have carved out a bubble about 20 pc in diameter in the surrounding gas and dust. This ring of gas and dust is compressed and heated, making the dust glow in the IR.

Triggered Star Formation by Supernovae

During the violent death of a massive star after it has left the main sequence the core collapses and causes the release of vast quantities of particles and energy that blow the star apart.

The **star's outer layers are blasted into space** at speeds of several thousand kilometers per second.

The supernova winds shocks and compresses the interstellar gas it encounters. The ejected material and the swept up material form a **supernova remnant.**



A composite *Spitzer, HST* and *Chandra* Image of the Cas A supernova remnant. In the roughly 300 years since the supernova explosion, a shock wave has expanded about 3 pc outward in all directions from the explosion site.

Triggered Star Formation by Supernovae

The compression of the interstellar medium by an expanding SNR shockwave may trigger star formation.

Supernovae also **eject heavy metals** into the ISM that are not produced in any other way.

Some meteorites found on Earth contain radioactive elements that suggest the Sun was formed after a supernova explosion in the near vicinity triggered star formation.

The Canis Major R1 Association. The shock wave from a supernova has ionized gas in this interstellar cloud and compressed it to trigger star formation.