Astrophysical Objects

Star Formation

An introduction to modern Astrophysics chapter 12

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HII regions

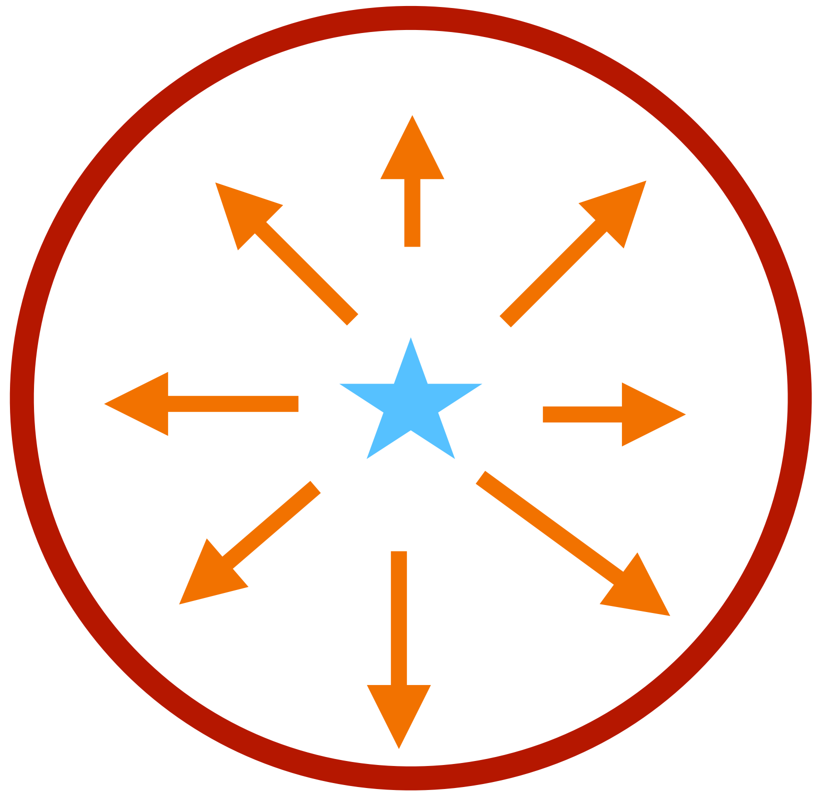
When hot, massive stars reach the ZAMS with **O or B spectral types**, they are shrouded in a **cloak of gas and dust.**

The bulk of their **radiation is emitted in the ultraviolet** portion of the electromagnetic spectrum. Those photons that are produced with energies in excess of 13.6 eV can **ionize the ground-state hydrogen** gas (H I) in the ISM that still surrounds the newly formed star.

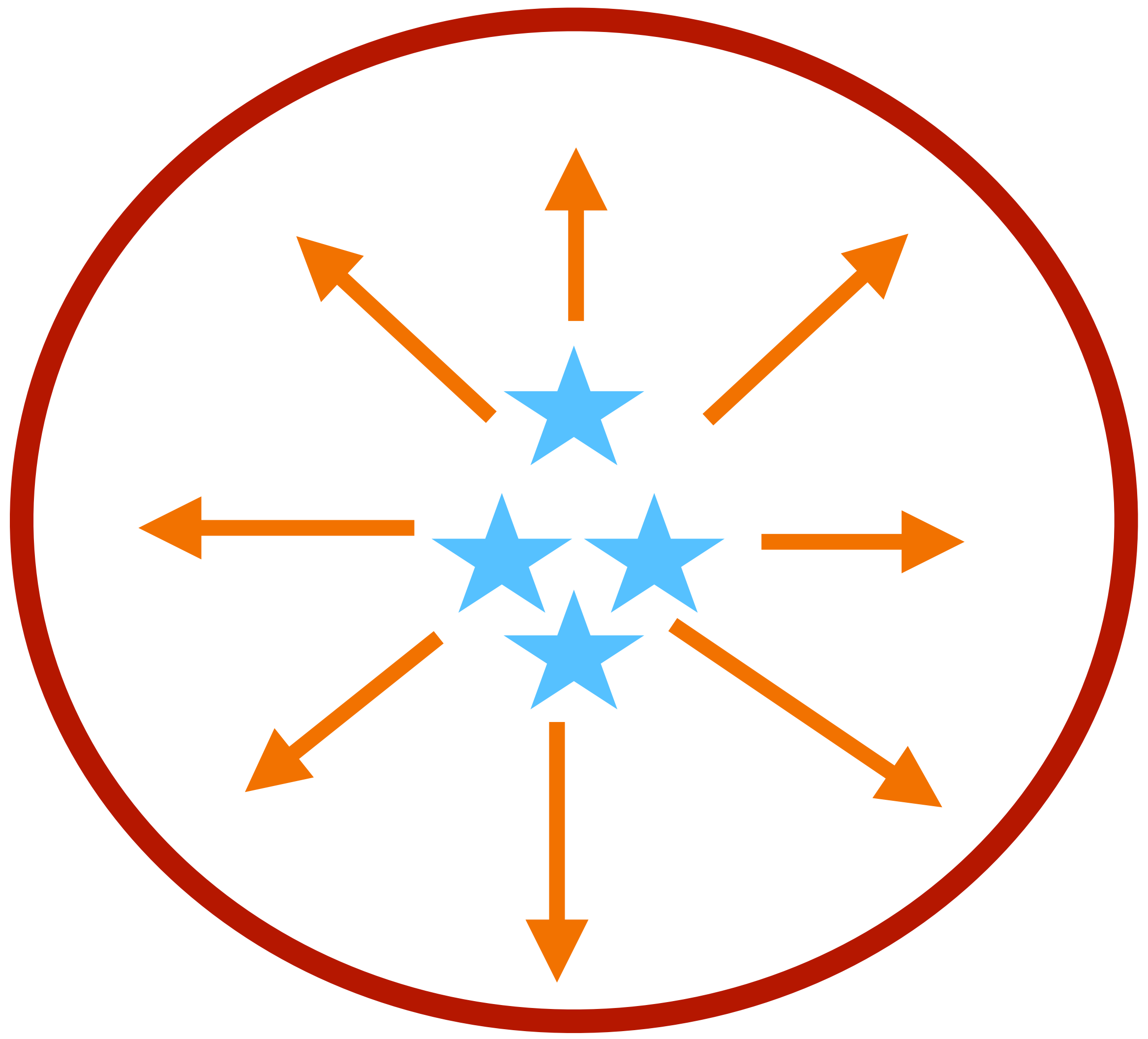
Of course, if these **H II regions** are in **equilibrium, the rate of ionization must equal the rate of recombination;** photons must be absorbed and ions must be produced at the same rate that free electrons and protons recombine to form neutral hydrogen atoms.

When **recombination** occurs, the **electron** does not necessarily fall directly to the ground state but **can cascade downward, producing a number of lower-energy photons,** many of which will be in the visible portion of the spectrum.

HII region, with O, B star



Large HII region, with many O, B stars



HII regions

The Trapezium cluster

The dominant visible wavelength photon produced in this way results from the transition between n = 3 and n = 2, the **red line of the Balmer series (Hα)**.

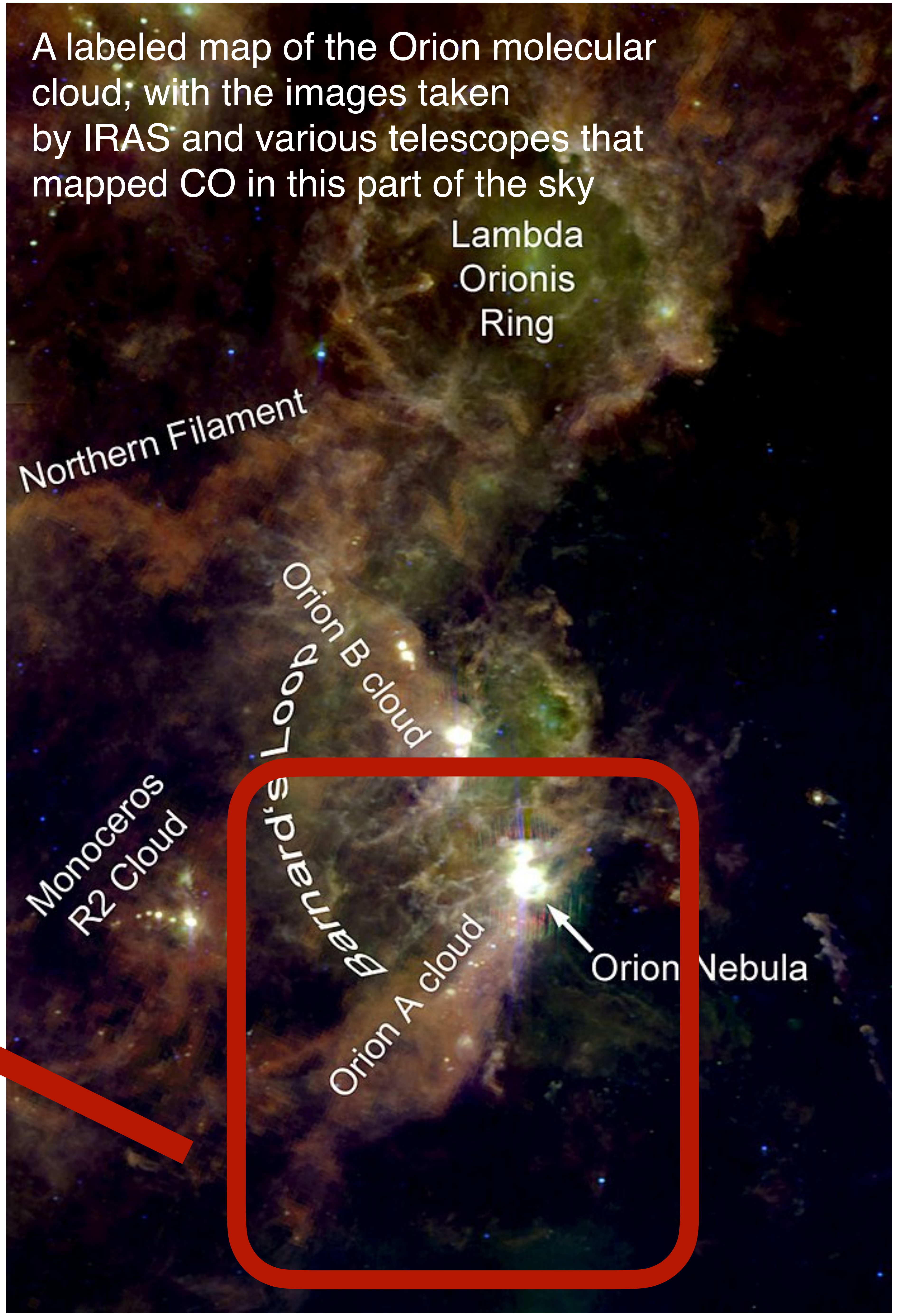
These are a type of **emission nebulae**.

One of the more famous H II regions is the **Orion nebula** (M42), found in the sword of the Orion constellation. M42 is part of the Orion A complex, which also contains a giant molecular cloud (OMC 1) and a very young cluster of stars (the Trapezium cluster). The first protostar candidates were discovered in this region as well.

HI regions

Orion A complex

Infrared image by the Herschel telescope



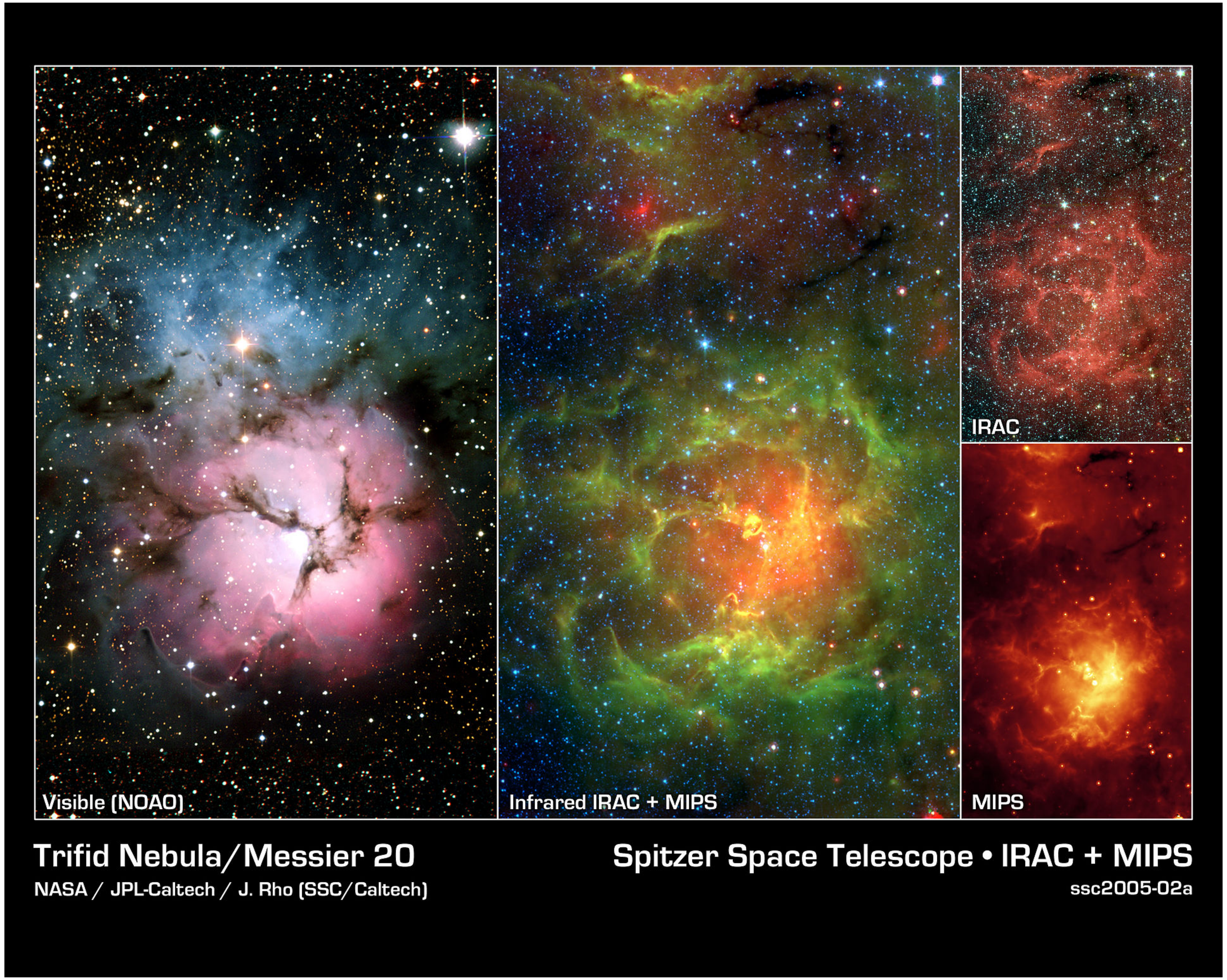
HII regions

Star formation region
W51 in infrared

- **Very often an electron cascades through several energy levels, thereby emitting many photons.**
- The HII region is one phase of the ISM which can be studied by the **visible light** emitted by it.
- When an electron makes a transition between two relatively high levels (say from $n = 100$ to $n = 99$), a **radio photon** is emitted.
- Additionally, the hot gas in the HII regions also emits bremsstrahlung with a continuous spectrum in the radio range.
- HII regions also radiate in emission lines from **partially ionized atoms of elements like carbon, nitrogen and oxygen.**

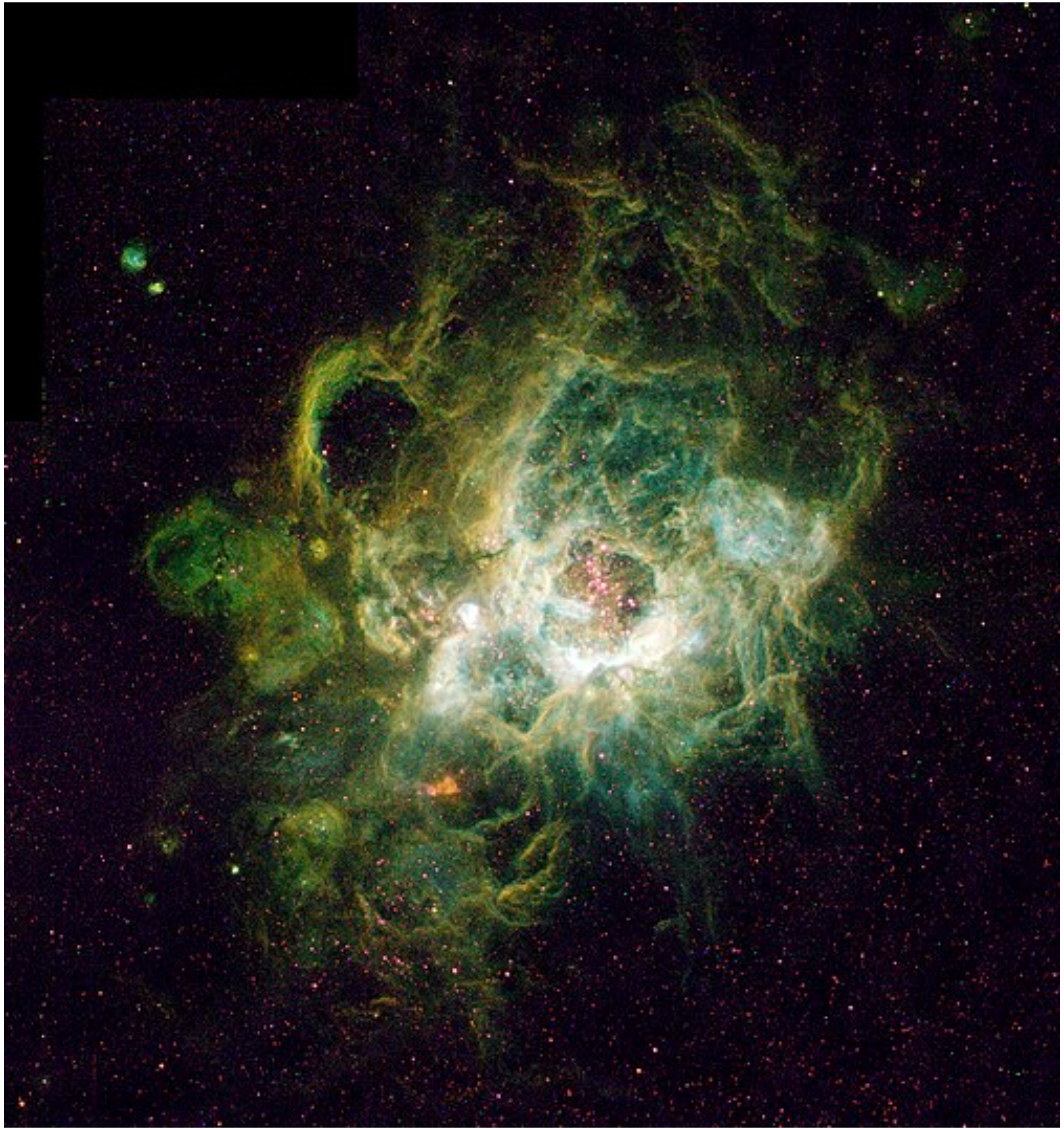
HII regions

- Star formation region in the Large Magellanic Cloud



HII regions

NGC 604, a giant H II region in the Triangulum Galaxy



HII regions

The **size of an H II region** can be estimated by considering the requirement of **equilibrium**.

Let N be the number of photons *per second* produced by the O or B star with sufficient energy to ionize hydrogen from the ground state ($\lambda < 91.2$ nm). Assuming that all of the energetic photons are ultimately absorbed by the hydrogen in the H II region, the **rate of photon creation must equal the rate of recombination.** If this equilibrium condition did not develop, the size of the region would continue to grow as the photons traveled ever farther before encountering un-ionized gas.

Next, let $\alpha n_e N_H$ be the number of **recombinations *per unit volume per second*,** where α is a quantum-mechanical recombination coefficient that describes the likelihood that an electron and a proton can form a hydrogen atom, given their number densities (obviously, the more electrons and protons that are present, the greater the chance of recombination; hence the product $n_e N_H$).

At about 8000 K, a temperature characteristic of H II regions, $\alpha = 3.1 \times 10^{-19}$ m^3 s^{-1}.

If we assume that the gas is composed **entirely of hydrogen** and is neutral, then for every ion produced, one electron must have been liberated, or $n_e = N_H$.

HII regions

With this equality, the expression for the recombination rate can be multiplied by the **volume of the H II region**, assumed here to be **spherical,** and then set equal to the number of ionizing photons produced per second. Finally, solving for the radius of the H II region gives

$$r_S \simeq \left(\frac{3N}{4\pi\alpha}\right)^{1/3} n_H^{-2/3}.$$

r_S is called the **Strömgren radius.**

- The HII regions are often found to be approximately spherical in shape and are known as ***Strömgren spheres*.**

HII regions

Example: The effective temperature and luminosity of an **O6 star** are $T_e \simeq 45{,}000$ K and $L \simeq 1.3 \times 10^5\ L_\odot$, respectively. According to Wien's law, the peak wavelength of the blackbody spectrum is given by

$$\lambda_{\max} = \frac{0.0029 \text{ m K}}{T_e} = 64 \text{ nm}.$$

Since this is significantly shorter than the 91.2-nm limit necessary to produce ionization from the hydrogen ground state, it can be assumed that most of the photons created by an O6 star are capable of causing ionization.

The energy of one 64-nm photon can be calculated giving

$$E_\gamma = \frac{hc}{\lambda} = 19 \text{ eV}.$$

Now, assuming for simplicity that all of the emitted photons have the same (peak) wavelength, the total number of photons produced by the star per second is just

$$N \simeq L/E_\gamma \simeq 1.6 \times 10^{49} \text{ photons s}^{-1}.$$

Lastly, taking $n_H \sim 10^8\ \text{m}^{-3}$ to be a typical value an H II region, we find $\mathbf{r_S \simeq 3.5}$ **pc.**

Values of r_S range from less than **0.1 pc to greater than 100 pc.**

The effects of massive stars

As a **massive star forms**,

- the protostar will initially appear as an **infrared source** embedded inside the molecular cloud.
- With the rising temperature, first the **dust will vaporize**,
- then the **molecules will dissociate,**
- and finally, as the star reaches the main sequence, the **gas immediately surrounding it will ionize**, resulting in the creation of an H II region inside of an existing H I region.
- Now, **because of the star's high luminosity, radiation pressure** will begin to drive significant amounts of mass loss, **which then tends to disperse the remainder of the cloud.**

If several O and B stars form at the same time, it may be that much of the mass that has not yet become gravitationally bound to more slowly forming low-mass protostars will be driven away, **halting any further star formation**.

If the **cloud was originally marginally bound** (near the limit of criticality), the loss of mass will diminish the potential energy term in the virial theorem, with the result that the **newly formed cluster of stars and protostars will become unbound** (i.e., the stars will tend to **drift apart**).

The effects of massive stars

The Carina Nebula is a large bright nebula that surrounds several clusters of stars. It contains two of the most massive and luminous stars in our Milky Way galaxy, Eta Carinae and HD 93129A. Located 7500 light years away, the nebula itself spans some 260 light years across, about 7 times the size of the Orion Nebula.

Being brighter than one million Suns, Eta Carinae (the brightest star in this image) is the most luminous star known in the Galaxy, and has most likely a mass over 100 times that of the Sun.

Radiation from the bright stars is shredding the dust clouds in the lower part of the images.

The effects of massive stars

Another famous example of the effects of ionizing radiation of nearby massive stars is the production of the pillars in M16, the Eagle Nebula.

The left most pillar is more than 1 pc long from base to top. Ionizing radiation from massive newborn stars off the top edge of the image are causing the gas in the cloud to photoevaporate.

Hubble Space Telescope

James Webb Telescope

OB Associations

Groups of stars that are dominated by O and B main-sequence stars are referred to as **OB associations**.

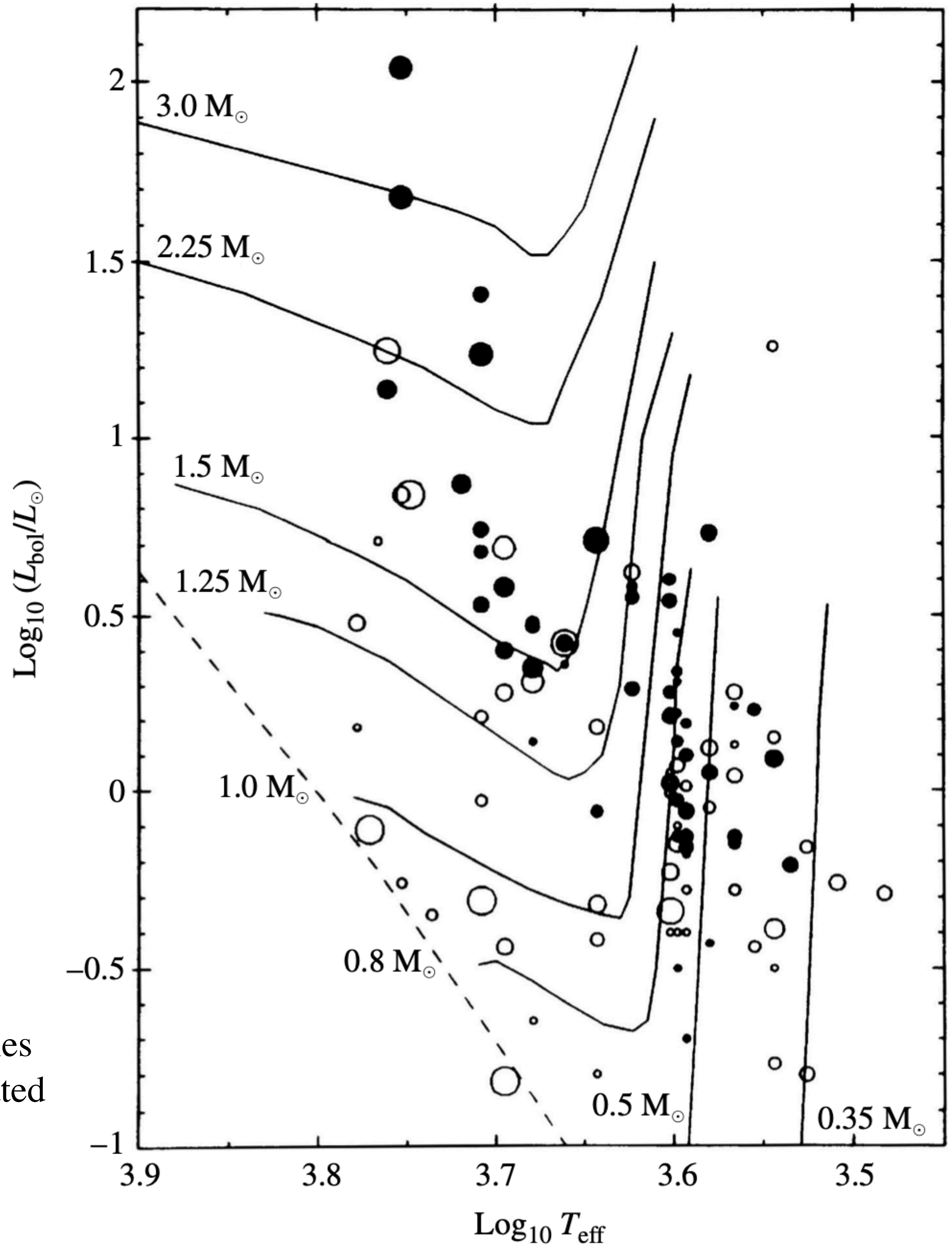
Studies of their individual kinematic velocities and masses generally lead to the conclusion that they **cannot remain gravitationally bound** to one another as permanent stellar clusters. One such example is the Trapezium cluster in the Orion A complex, believed to be less than 10 million years old. It is currently densely populated with stars ($> 2 \times 10^3$ pc^{-3}), most of which have masses in the range of 0.5 to 2.0 $M_\odot$.

Doppler shift measurements of the radial velocities of ^{13}CO show that the gas in the vicinity is very turbulent. Apparently, the nearby O and B stars are dispersing the gas, and the cluster is becoming unbound.

T Tauri stars

T Tauri stars are an important class of **low-mass pre-main-sequence objects** that represent a transition between stars that are still shrouded in dust (IR sources) and main-sequence stars.

T Tauri stars, named after the first star of their class to be identified, are characterized by unusual spectral features and by large and fairly **rapid irregular variations in luminosity**, with **timescales on the order of days**. The positions of T Tauri stars on the H–R diagram are shown in the Figure; theoretical pre-main-sequence evolutionary tracks are also included. The masses of T Tauri stars range from 0.5 to about 2 $M_\odot$.



The positions of T Tauri stars on the H–R diagram. The sizes of the circles indicate the rate of **rotation**. Stars with **strong emission lines** are indicated by filled circles, and weak emission line stars are represented by open circles. Theoretical pre-main-sequence evolutionary tracks are also included.

T Tauri stars

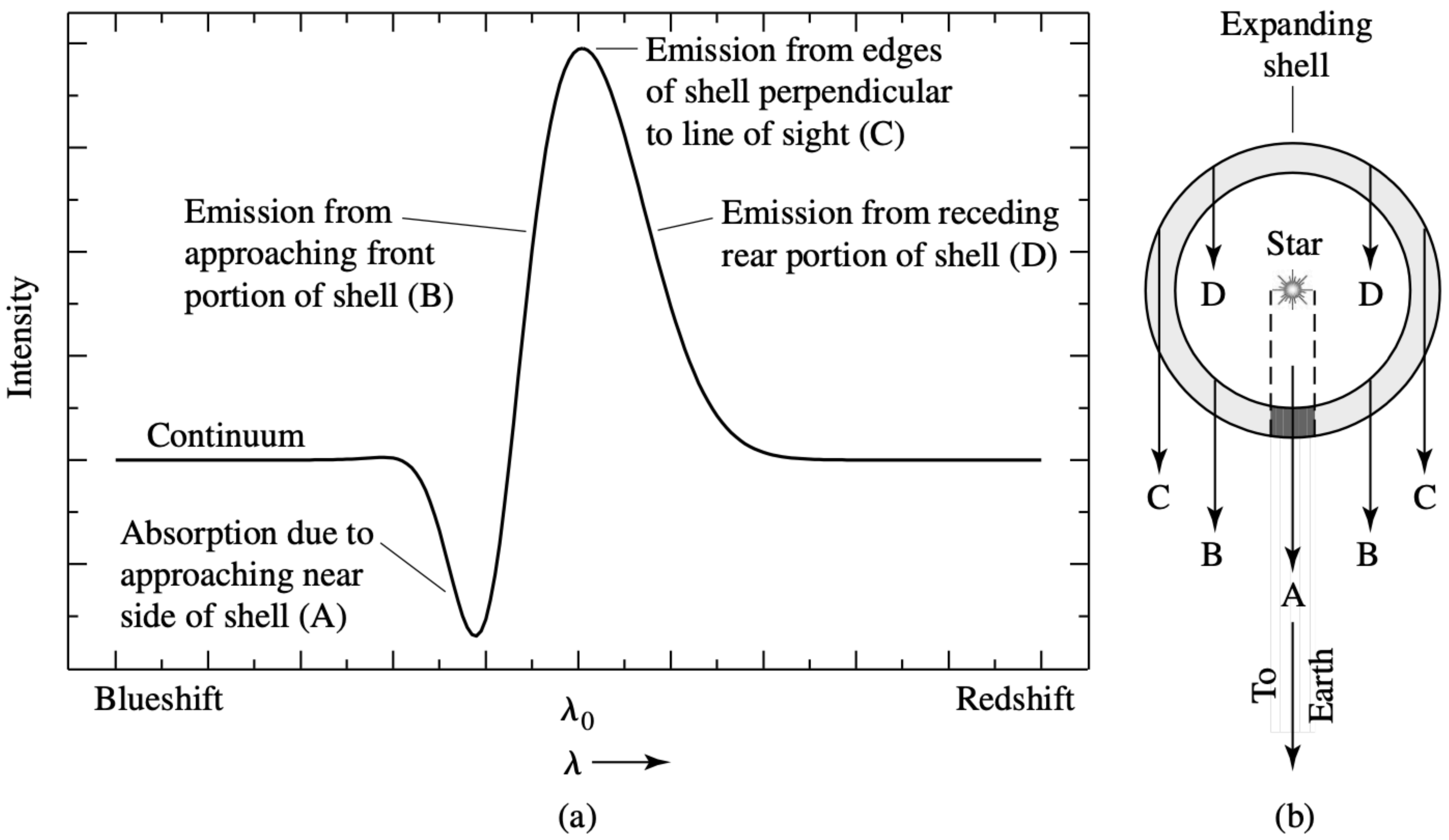
Many T Tauri stars exhibit **strong emission lines** from hydrogen (the Balmer series), from Ca II (the H and K lines), and from iron, as well as absorption lines of lithium.

Interestingly, forbidden lines of [O I] and [S II] are also present in the spectra of many T Tauri stars. The existence of forbidden lines in a spectrum is an **indication of extremely low gas densities.**

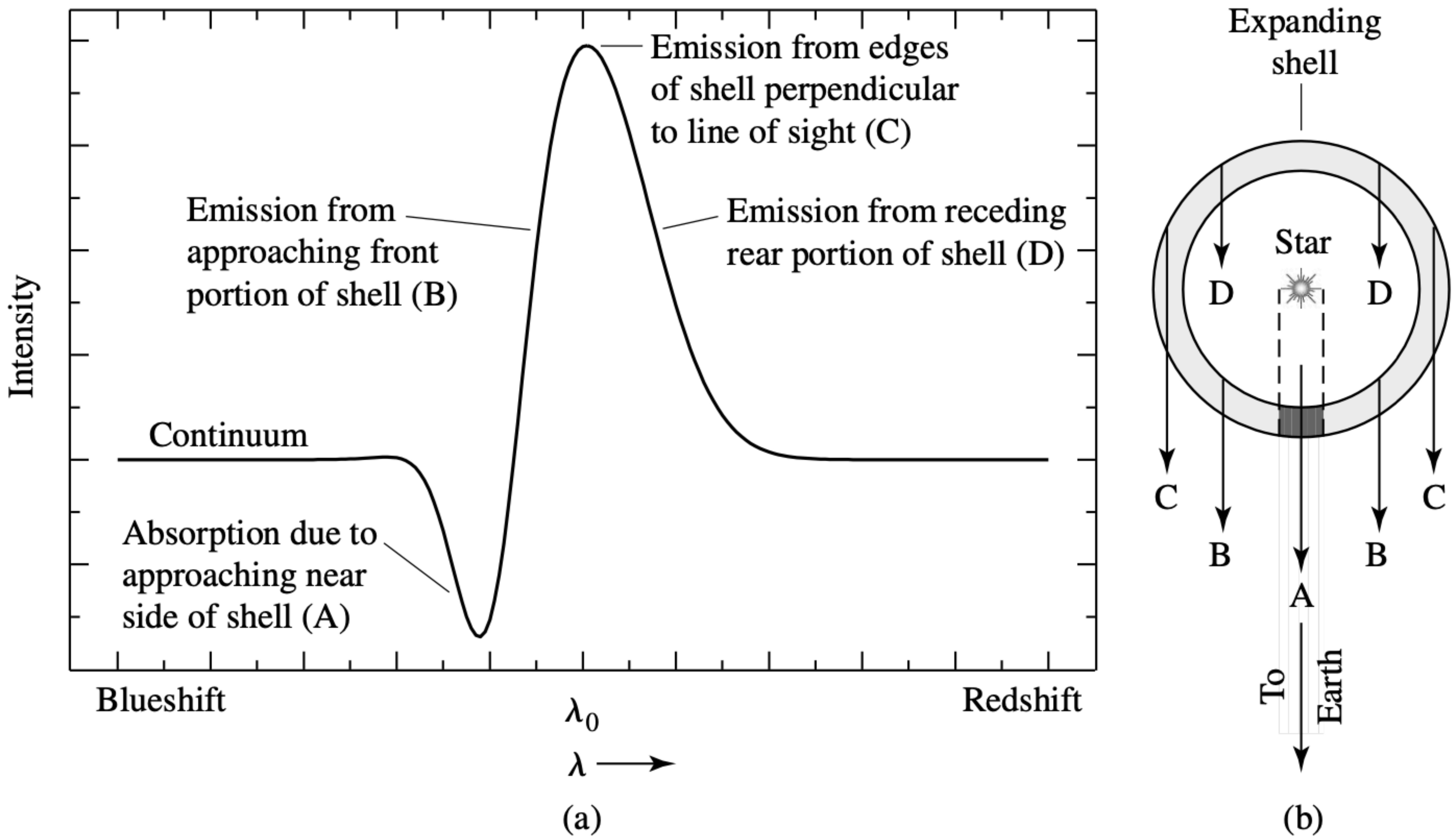
Information is also contained in the ***shapes* of those lines** as a function of wavelength.

The Hα line often exhibits the characteristic shape shown in the Figure. Superimposed on a rather **broad emission peak** is an **absorption trough** at the short-wavelength edge of the line.

This unique line shape is known as a **P Cygni profile**, after the first star observed to have emission lines with blueshifted absorption components.



T Tauri stars



(a) A spectral line exhibiting a P Cygni profile is characterized by a broad emission peak with a superimposed blueshifted absorption trough.

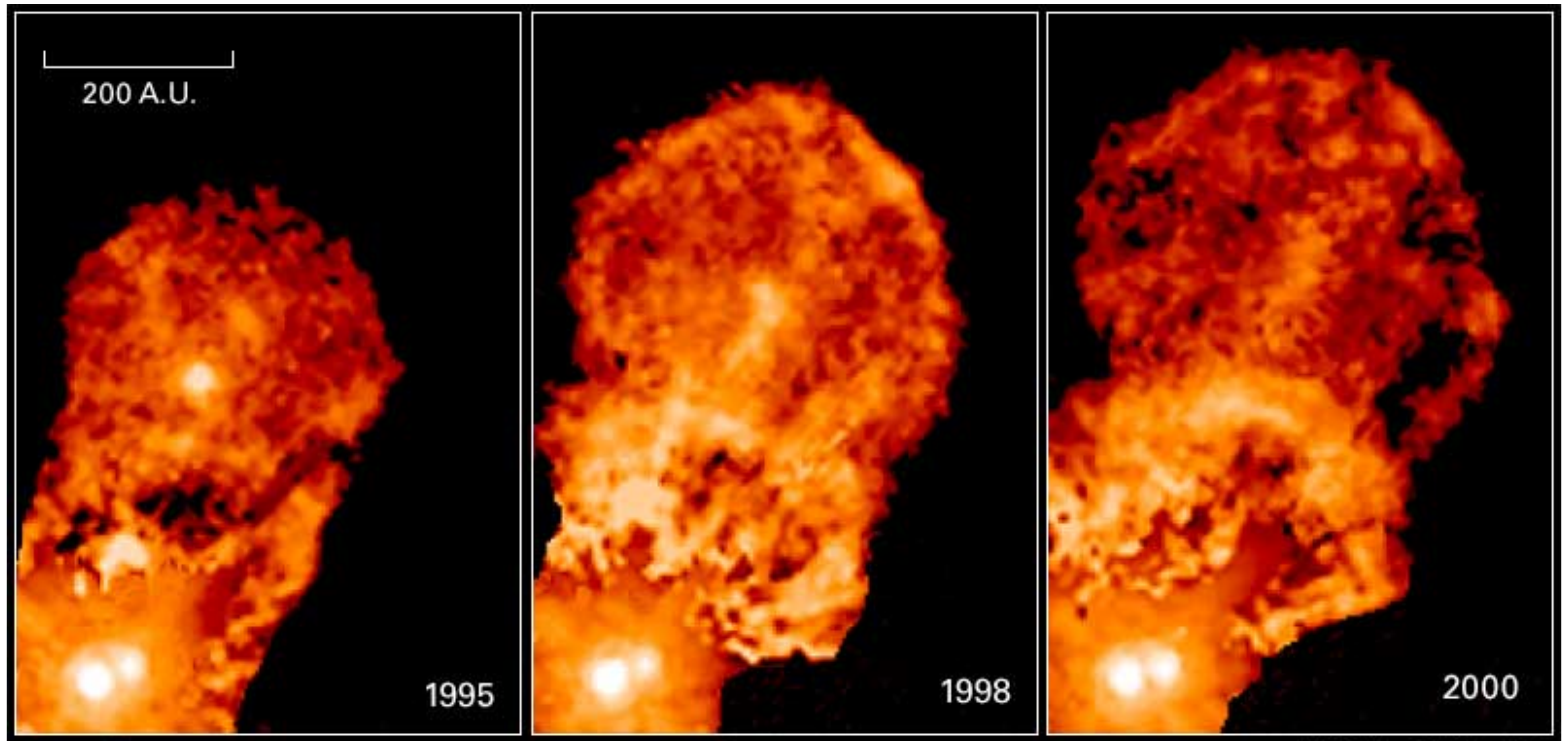
(b) (b) A **P Cygni profile is produced by an expanding mass shell.** The emission peak is due to the outward movement of material perpendicular to the line of sight, whereas the blueshifted absorption feature is caused by the approaching matter in the shaded region, intercepting photons coming from the central star.

T Tauri stars

The interpretation given for the existence of P Cygni profiles in a star's spectrum is that the **star is experiencing significant mass loss.**

The mass loss rates of T Tauri stars average about $\dot{M} = 10^{-8}\ M_\odot\ yr^{-1}$.

In some extreme cases, line profiles of T Tauri stars have gone from P Cygni profiles to ***inverse* P Cygni profiles** (redshifted absorption) on timescales of days, **indicating mass accretion rather than mass loss. Mass accretion rates appear to be on the same order as mass loss rates.** Apparently the environment around a T Tauri star is very unstable.



Hot Gas Bubble Ejected by Binary Star XZ Tauri
NASA and J. Krist (STScI) • STScI-PRC00-32

FU Orionis stars

In some instances, it appears that T Tauri stars have gone through very **significant increases in mass** accretion rates, reaching values on the order of $\dot{M} = 10^{-4}\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$.

At the same time the l**uminosities of the stars increase by four magnitudes or more**, with the increases **lasting for decades**.

The first star observed to undergo this abrupt increase in accretion was FU Orionis, for which the **FU Orionis stars** are named.

Apparently, instabilities in a circumstellar accretion disk around an FU Orionis star can result in on the order of $0.01\ \mathrm{M}_\odot$ being dumped onto the central star over the century or so duration of the outburst. During that time **the inner disk can outshine the central star by a factor of 100 to 1000**, while **strong, high-velocity winds** in excess of $300\ \mathrm{km\ s}^{-1}$ occur.

It has been suggested that T Tauri stars may go through several FU Orionis events during their lifetimes.

Herbig Ae/Be stars

Closely related to the T-Tauri stars are **Herbig Ae/Be stars**, named for George Herbig.

These pre-main-sequence stars are of spectral types A or B and have **strong emission lines**. Their masses range from **2 to 10 $M_\odot$** and they tend to be **enveloped in some remaining dust and gas.**

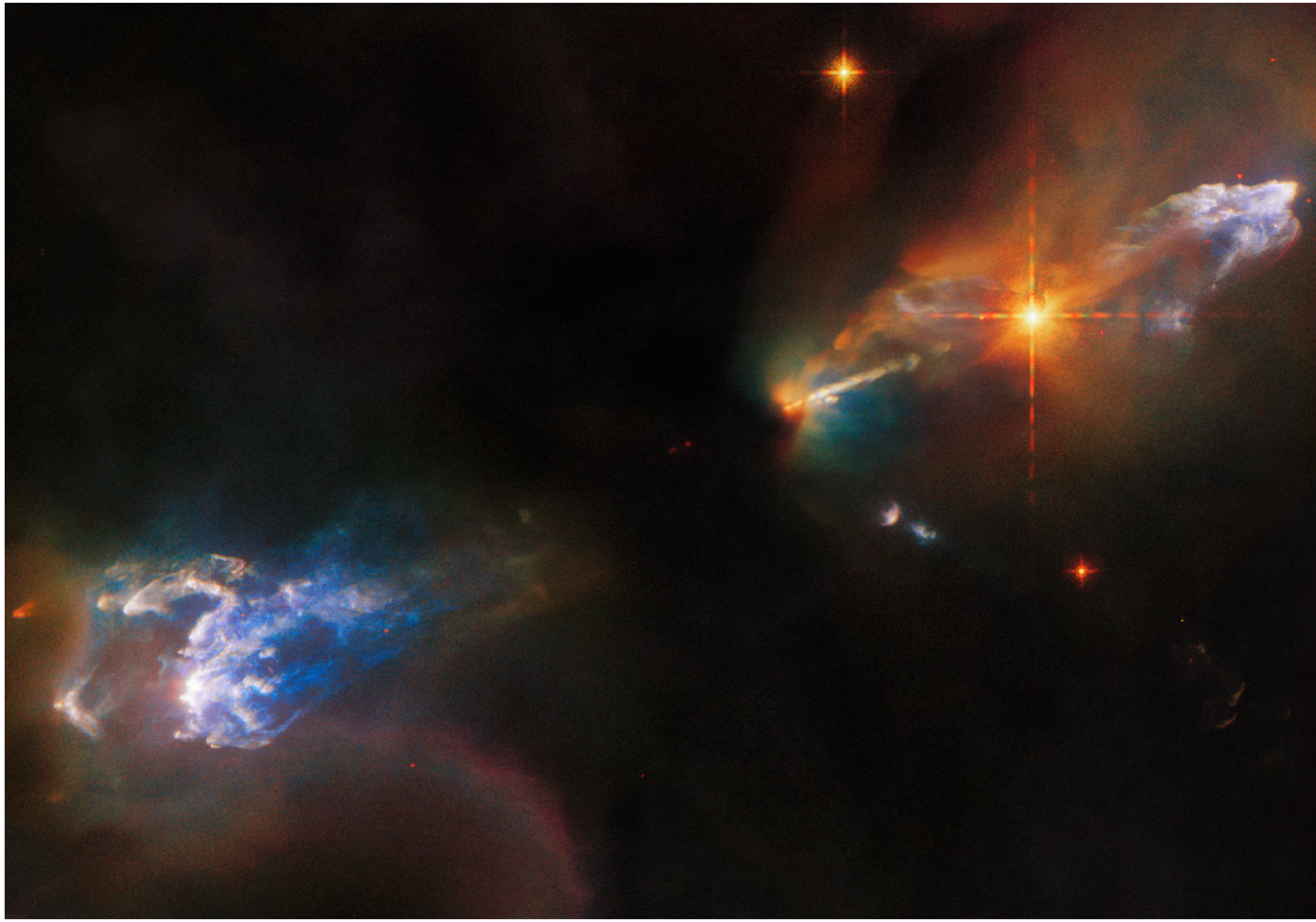
They have much shorter lifetimes compared to T Tauri stars, and there are fewer of them (higher mass).

Herbig Haro Objects

Closely Along with expanding shells, mass loss during pre-main-sequence evolution can also occur from **jets** of gas that are ejected in narrow beams in opposite directions.

Herbig–Haro objects, are apparently associated with the **jets produced by young protostars**, such as T Tauri stars. As the **jets expand supersonically into the interstellar medium, collisions excite the gas,** resulting in bright objects with emission-line spectra.

The Figure shows a Hubble Space Telescope image of the Herbig–Haro objects HH 1 and HH 2, which were created by material ejected at speeds of several hundred kilometers per second from a star shrouded in a cocoon of dust.



Herbig Haro Objects

The jets associated with another Herbig–Haro object, HH 47, are shown in Figure

James Webb Telescope

Herbig Haro Objects

Herbig–Haro (HH) objects are bright patches of nebulosity associated with newborn stars.
They are formed when narrow jets of partially ionised gas ejected by stars collide with nearby clouds of gas and dust at several hundred kilometres per second.
Herbig–Haro objects are **commonly found in star-forming regions**, and **several are often seen around a single star, aligned with its rotational axis.**
Most of them lie within about **one parsec (3.26 light-years) of the source,** although some have been observed several parsecs away.
HH objects are transient phenomena that **last around a few tens of thousands of years.**
They **can change visibly over timescales of a few years** as they move rapidly away from their parent star into the gas clouds of interstellar space (the interstellar medium or ISM).

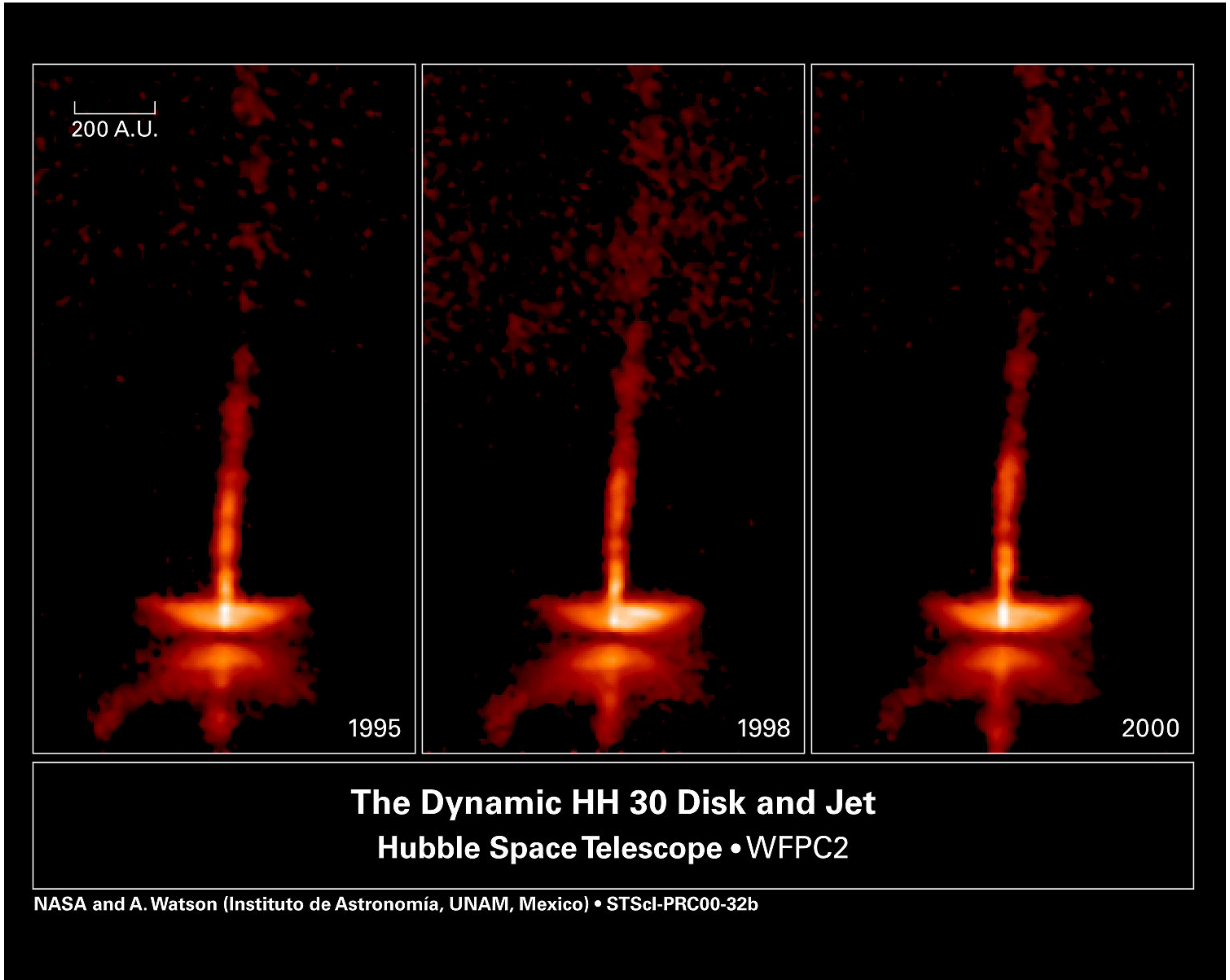
HH 24, image by Hubble Space Telescope

Herbig Haro Objects

Continuous emission is also observed in some protostellar objects and is due to the **reflection of light from the parent star.**

A **circumstellar accretion disk** is apparent around HH 30.

The surfaces of the disk are illuminated by the central star, which is again hidden from view behind the dust in the disk. Also apparent are jets originating from deep within the accretion disk, possibly from the central star itself.



Herbig Haro Objects

These **accretion disks** seem to be responsible for many of the characteristics associated with the protostellar objects,

- including emission lines,
- mass loss,
- jets,
- and perhaps even some of the luminosity variations.

Unfortunately, details concerning the physical processes involved are not fully understood.

An early model of the production of Herbig–Haro objects like HH 1 and HH 2 is shown in the Figure

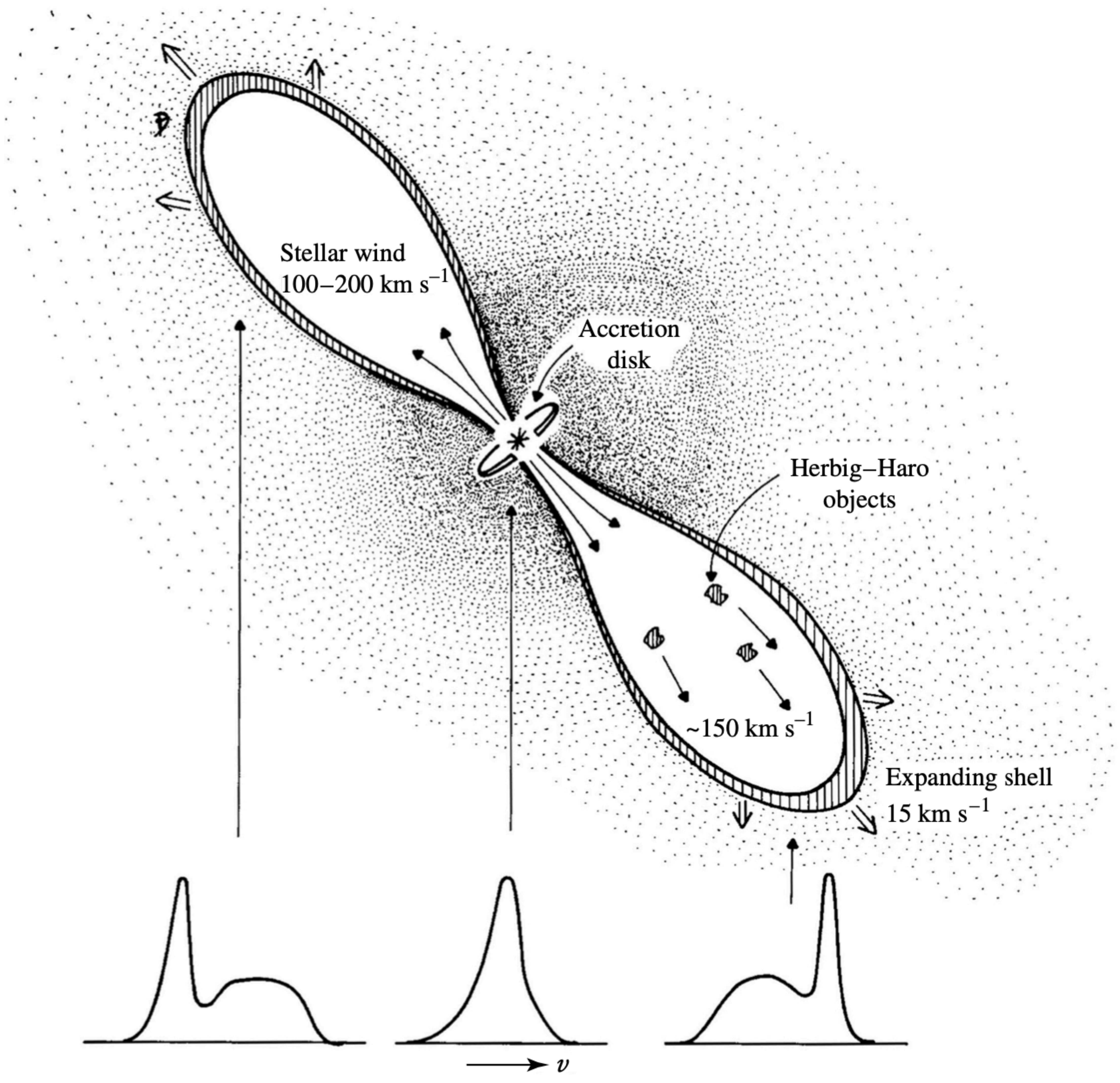
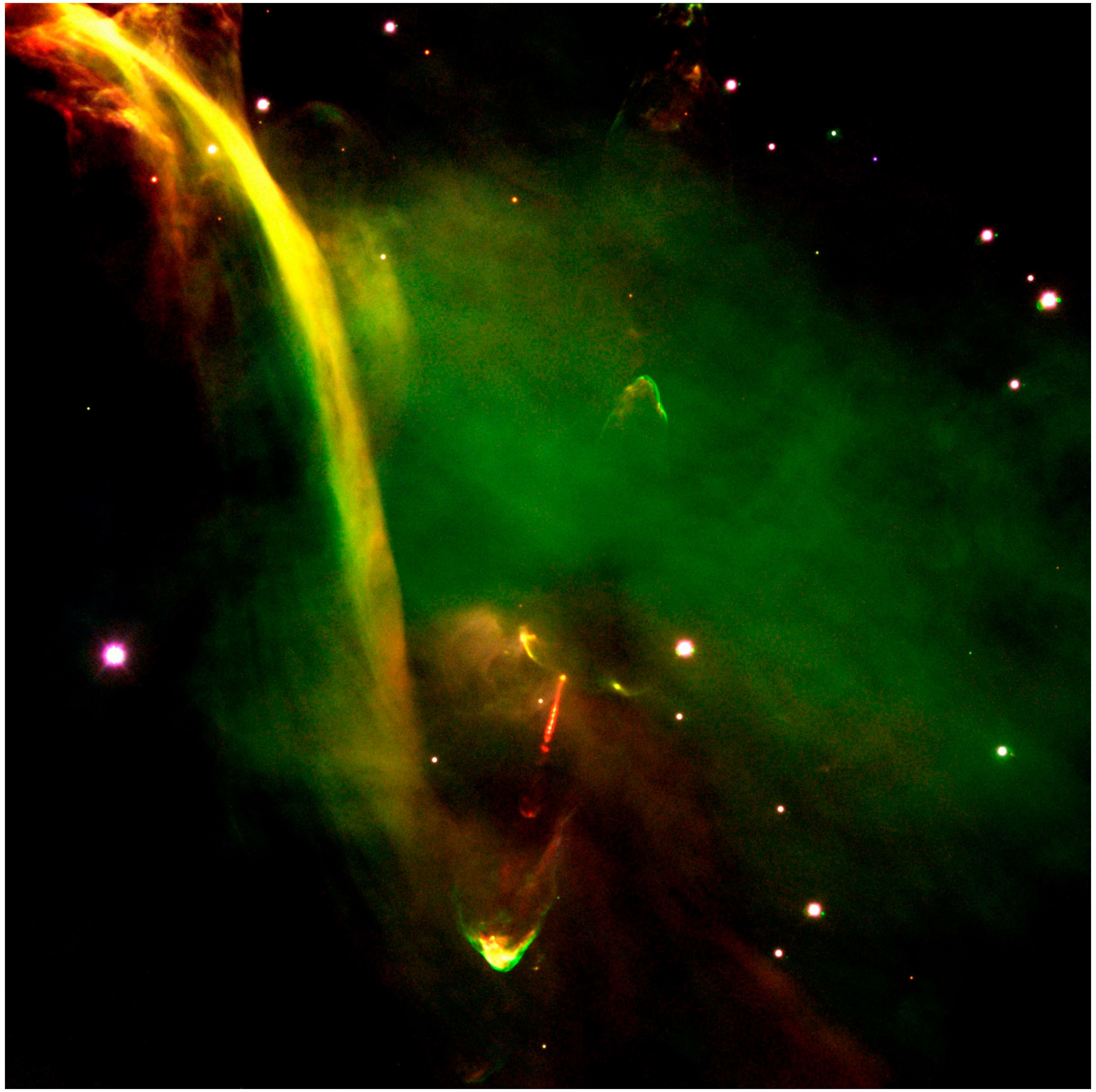
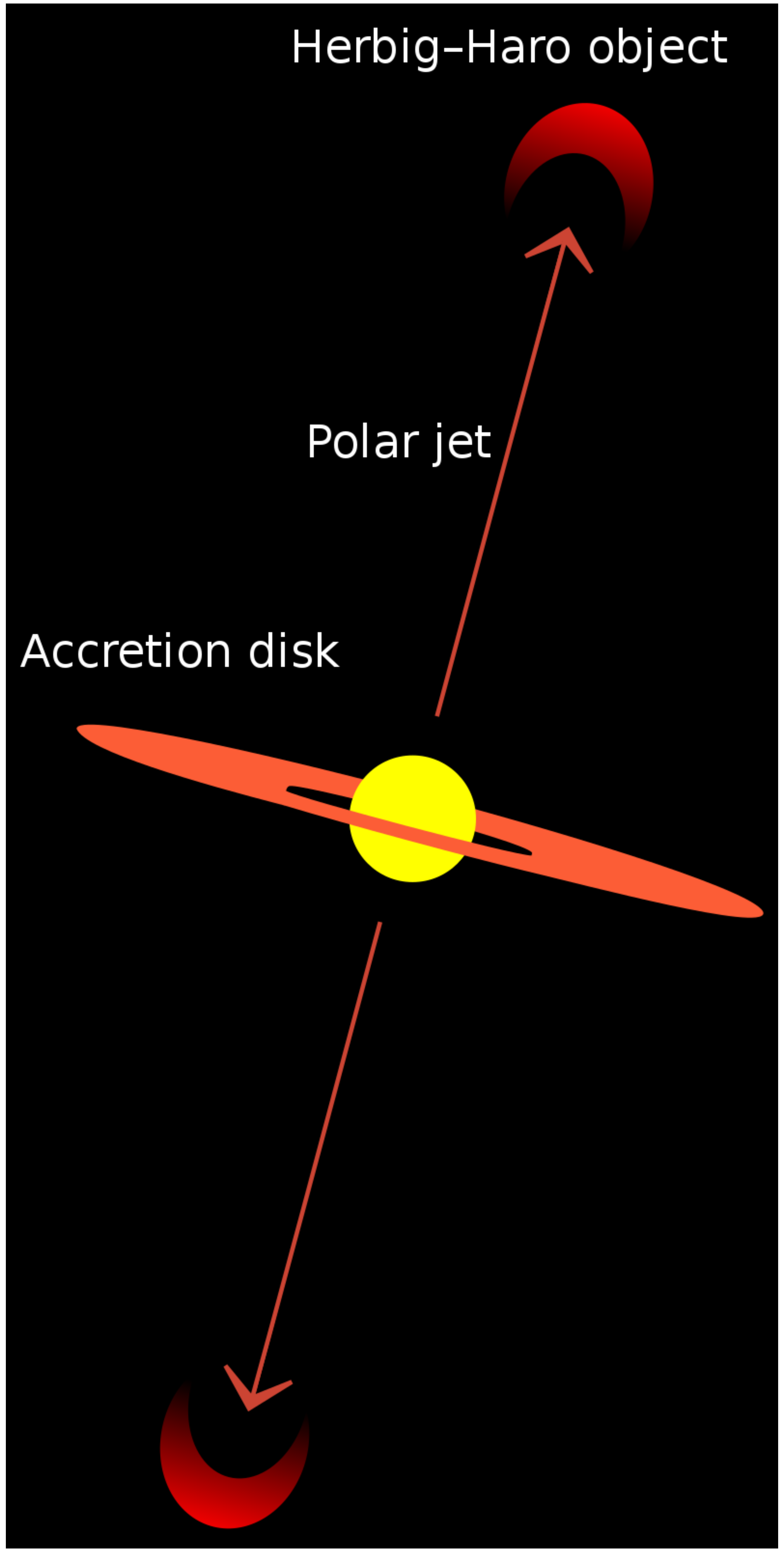


FIGURE 20 An early model of a T Tauri star with an accretion disk. The disk powers and collimates jets that expand into the interstellar medium, producing Herbig–Haro objects. (Figure adapted from Snell, Loren, and Plambeck, *Ap. J. Lett.*, *239*, L17, 1980.)

Herbig Haro Objects



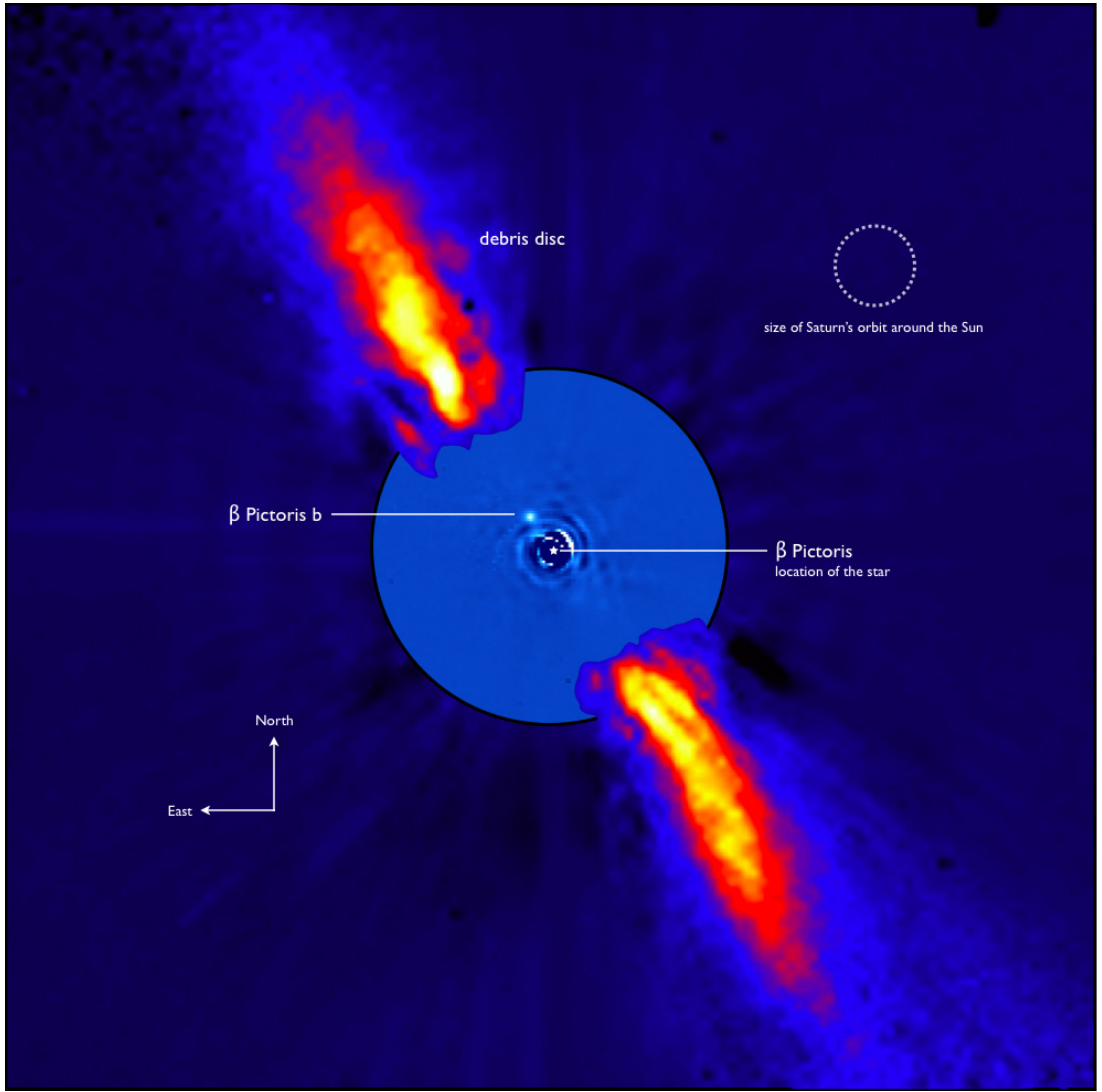
Herbig-Haro 34



Young stars with circumstellar disks

Observations have revealed that other young stars also possess circumstellar disks of material orbiting them. Two well-known examples are **Vega and β Pictoris**.

This composite image represents the close environment of Beta Pictoris as seen in **near infrared light.** This very faint environment is revealed after a very careful subtraction of the much brighter stellar halo.
The outer part of the image shows the reflected light on the dust disc, as observed in 1996;
the inner part is the innermost part of the system, as seen at 3.6 microns.
The newly detected source is more than 1000 times fainter than Beta Pictoris, aligned with the disc, at a projected distance of 8 times the Earth-Sun distance.



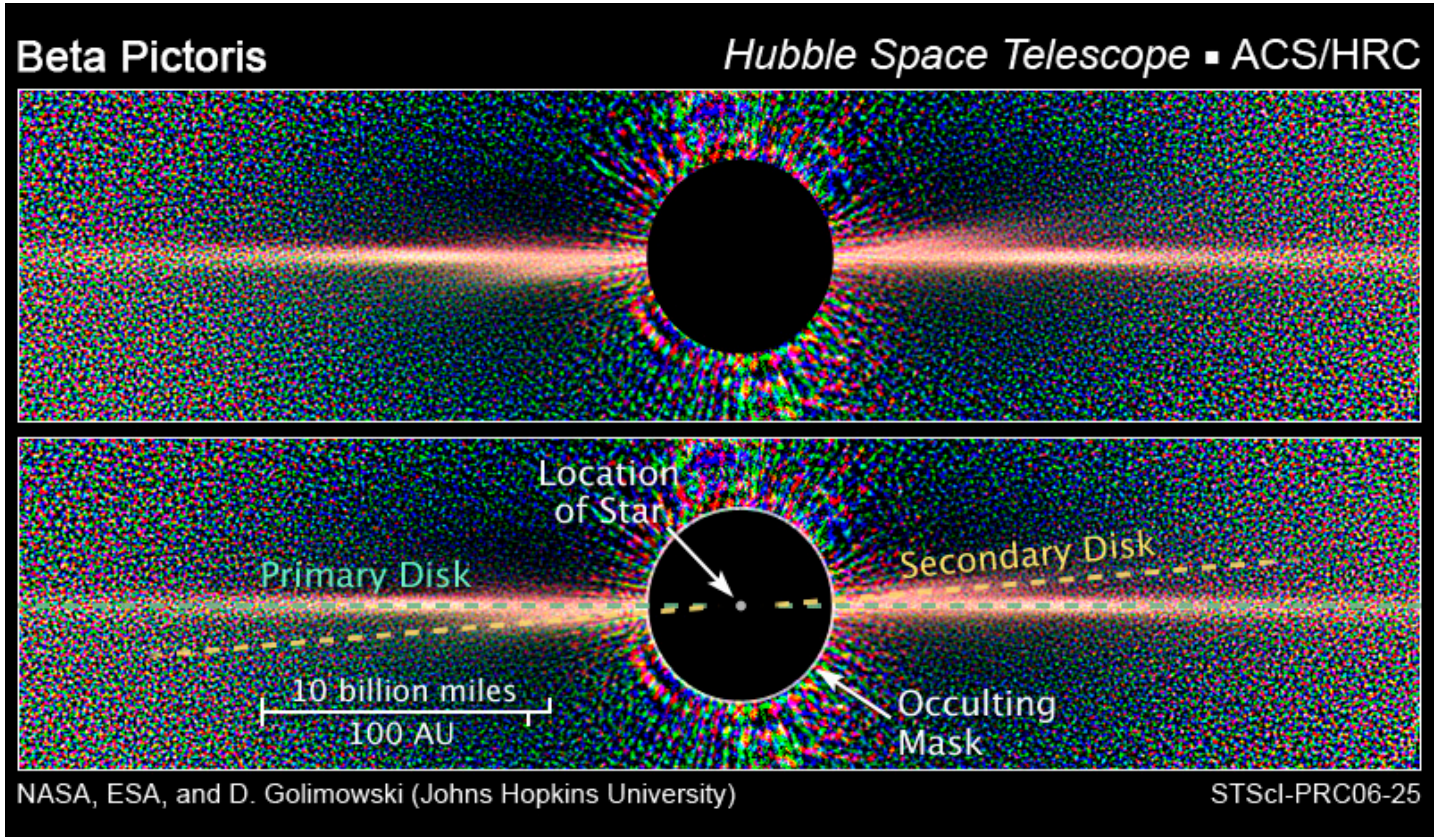
Young stars with circumstellar disks

Two planets, Beta Pictoris b, and Beta Pictoris c, through the use of **direct imagery.**

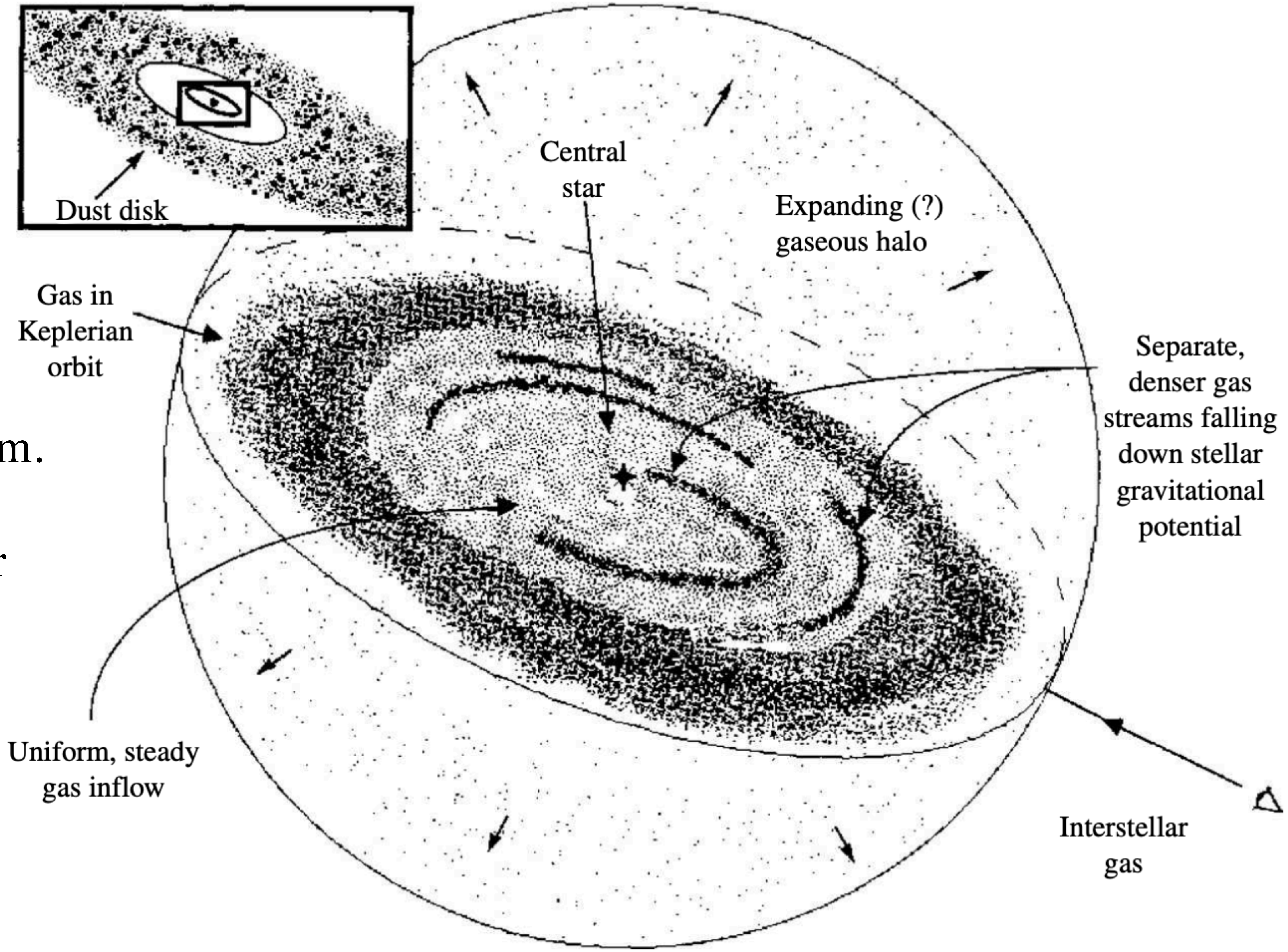
β Pic has also been observed in the ultraviolet lines of Fe II by the Hubble Space Telescope. It appears that **clumps of material are falling from the disk into the star at the rate of two or three per week.** Larger objects may be forming in the disk as well, possibly **protoplanets**.

It has been suggested that these disks may in fact be **debris disks** rather than accretion disks, meaning that the observed material is due to collisions between objects already formed in the disks.

Hubble images also show a **secondary dust disk,** which may point to a planet formed on an inclined orbit.



Young stars with circumstellar disks



An artist's conception of the β Pictoris system. Clumps of material appear to be falling into the star at the rate of two or three clumps per week. Some matter may also be leaving the system as an expanding halo.

Proplyds

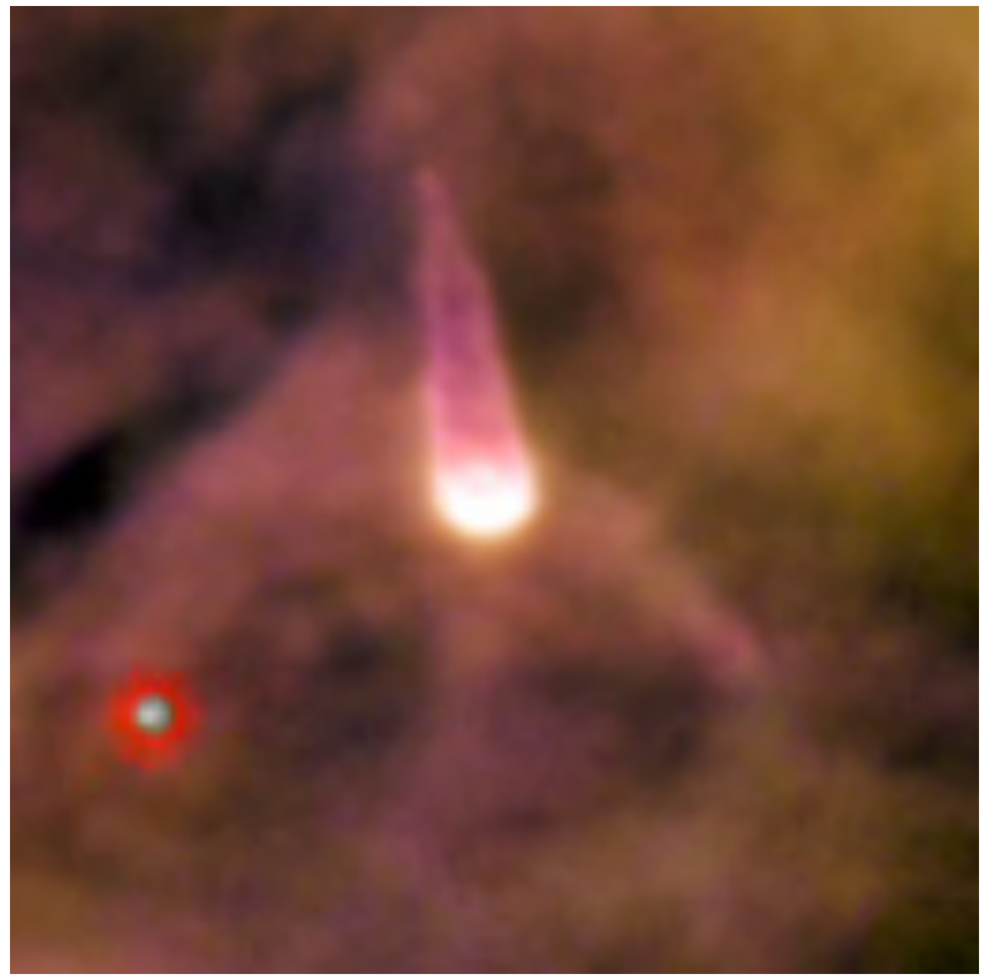
In 1993 the Hubble Space Telescope made observations of the Orion Nebula.

The images were obtained using the emission lines of Hα, [N II], and [O III].

Analysis of the data has revealed that **56 of the 110 stars brighter than V =21 mag are surrounded by disks of circumstellar dust and gas.** The circumstellar disks, termed **proplyds**, appear to be **protoplanetary disks associated with young stars** that are less than 1 million years old.

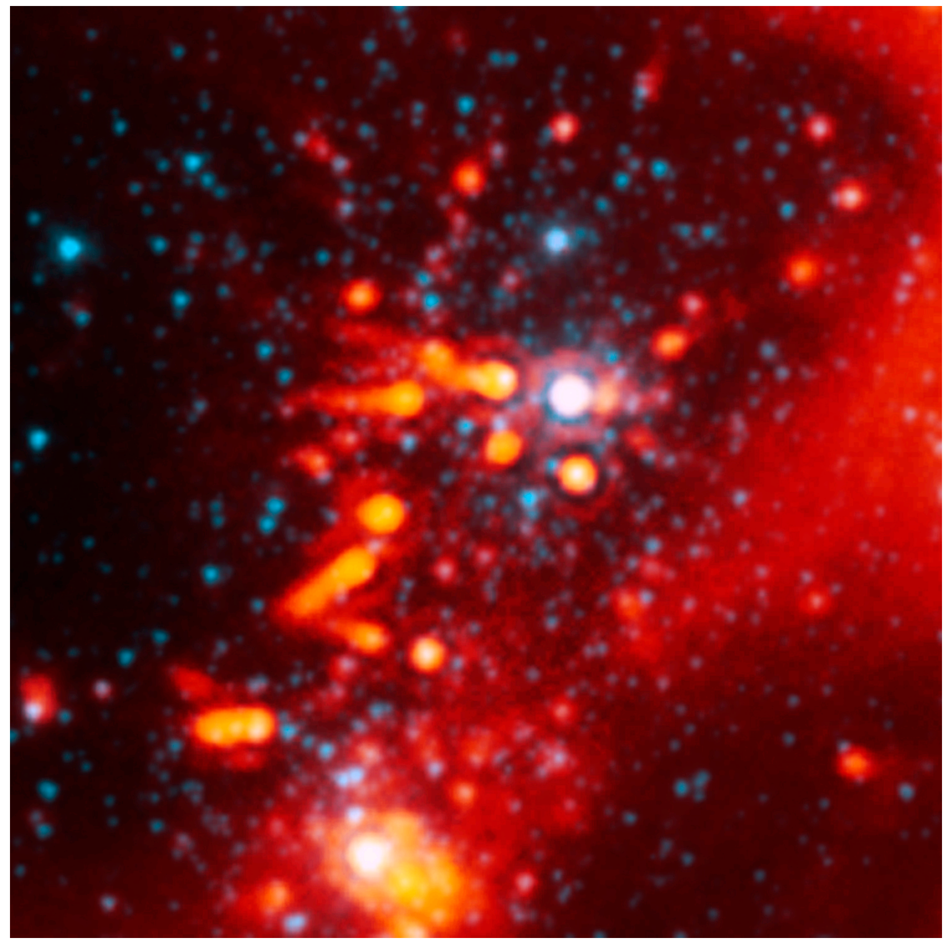
Based on observations of the ionized material in the proplyds, the disks seem to have masses much greater than 2×10^{25} kg (for reference, the mass of Earth is 5.974×10^{24} kg).

Proplyds

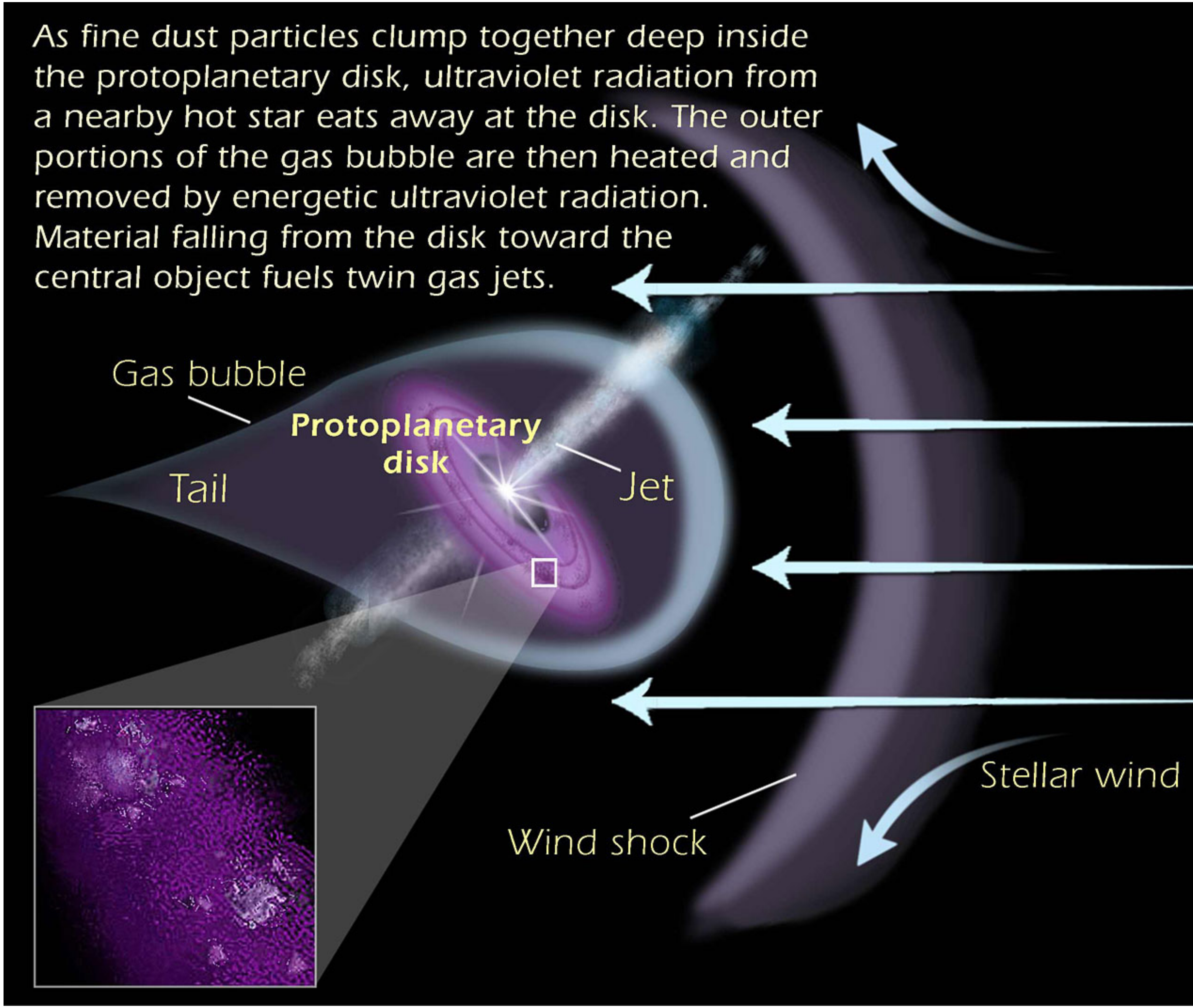


Harsh winds from extremely bright stars are blasting ultraviolet radiation at these stars and sculpting the gas and dust into its elongated shape.

Proplyds



Proplyds observed in infrared



Circumstellar disk formation

Disk formation is fairly common during the collapse of protostellar clouds.

Undoubtedly this is due to the **spin-up of the cloud as required by the conservation of angular momentum**.

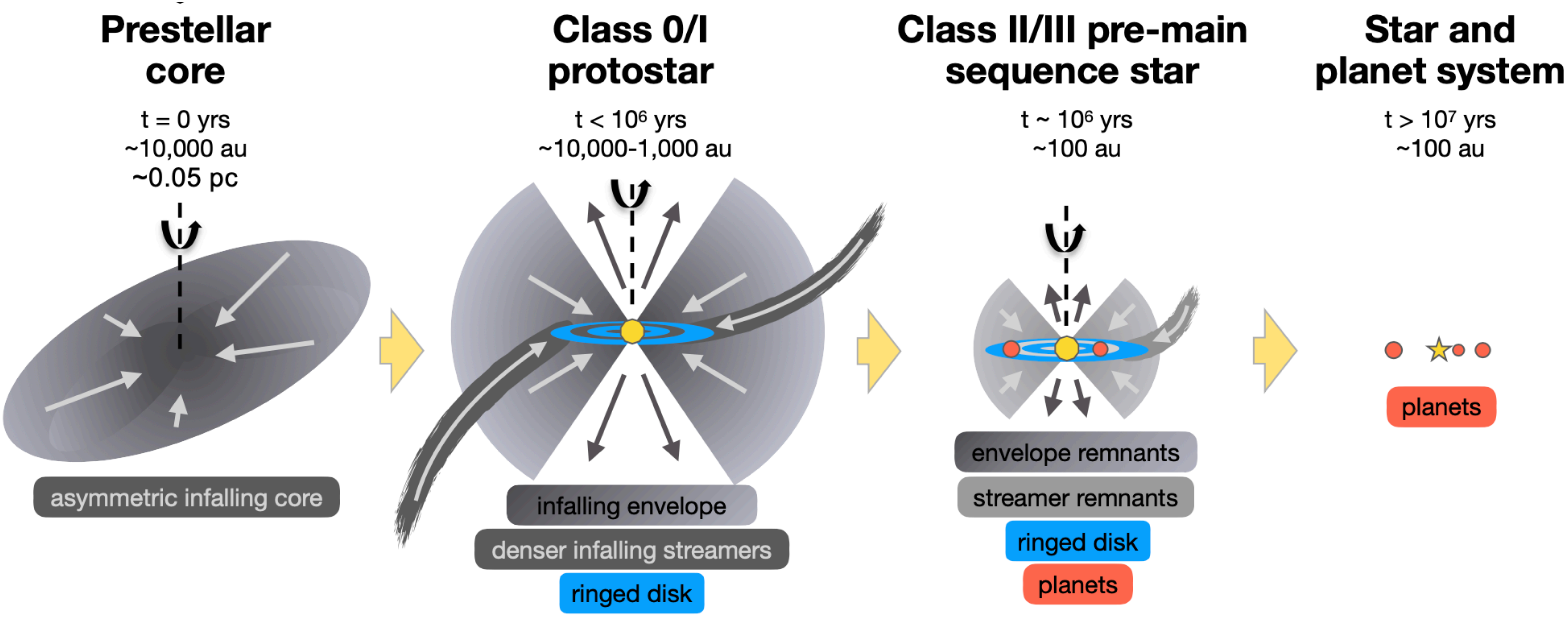
As the radius of the protostar decreases, so does its moment of inertia. This implies that in the absence of external torques, the protostar's angular velocity must increase. By including a centripetal acceleration term and requiring conservation of angular momentum, the collapse perpendicular to the axis of rotation can be halted before the collapse along the axis, resulting in disk formation.

A **problem** immediately arises when the effect of angular momentum is included in the collapse. Conservation of angular momentum arguments lead us to **expect that all main sequence stars ought to be rotating very rapidly, at rates close to breakup.** However, observations show that this is **not generally the case**.

Apparently the angular momentum is transferred away from the collapsing star. One suggestion is that **magnetic fields,** anchored to convection zones within the stars and coupled to ionized stellar winds, **slow the rotation** by applying torques. Evidence in support of this idea exists in the form of apparent solar-like coronal activity in the outer atmospheres of many T Tauri stars.

Along with the problems associated with rotation and magnetic fields, mass loss may also play an important role in the evolution of pre-main-sequence stars.

Summary



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