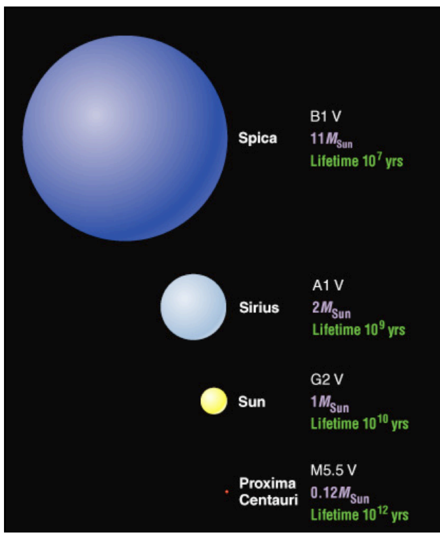


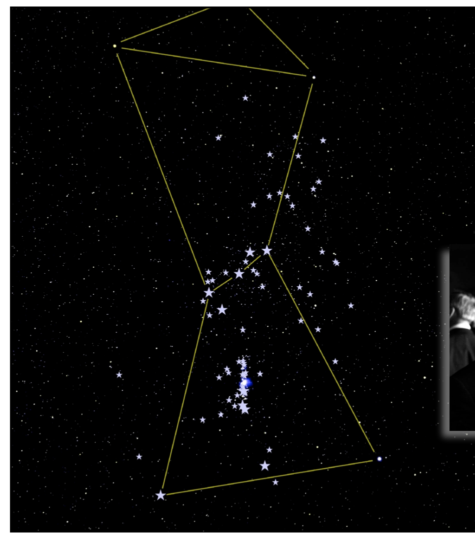





## Not all stars are equal.

*Hot massive stars live fast and die young.*

*They must be forming continously in other galaxies.*



Evidence for star formation in our own galaxy: associations of short lived, hot massive stars.

Victor Ambartsumian


## The Formation of Stars

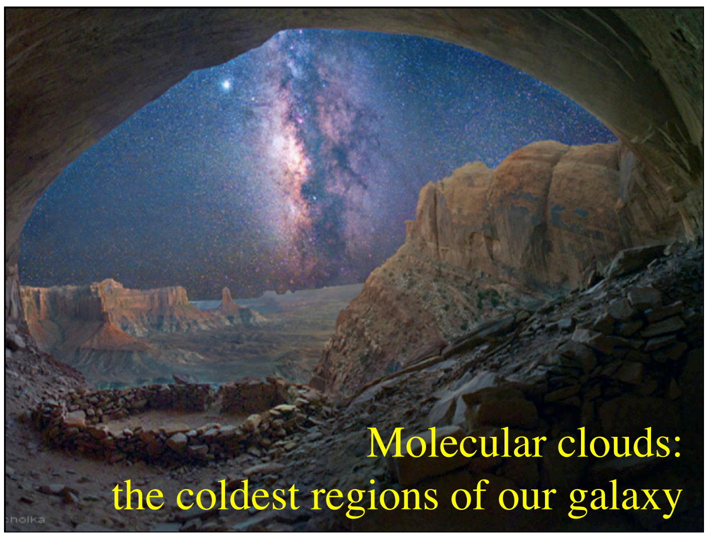
Because we know that there are many stars with ages much less than that of our Galaxy, news stars must be continually created. Our Sun was created 4.6 Billion years ago, at that time the Galaxy was already 8 Billion years old.

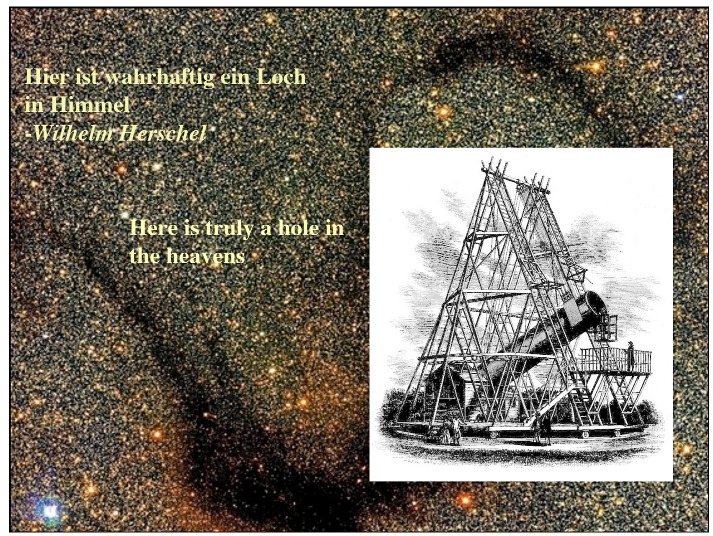
Estimated rate of star formation in our galaxy is a few stars per year.

To continually form stars, a source of hydrogen gas is needed.

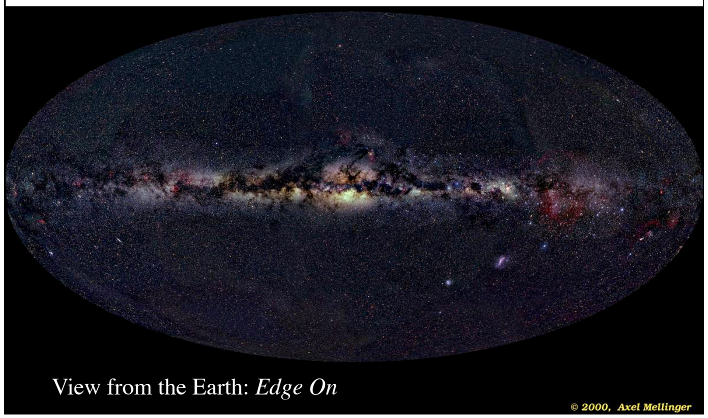
Our galaxy is fill with Hydrogen gas, with an *average* density of 1 atom per cubic centimeter

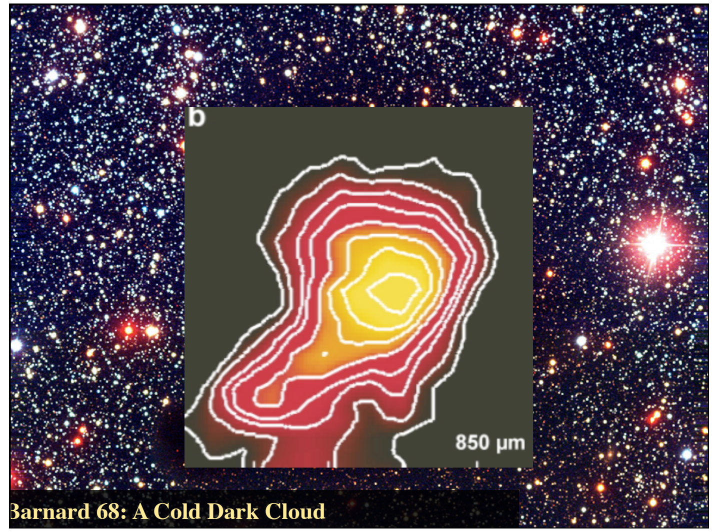
But how does this gas get converted into stars?



# The Milky Way in Visible Light




# Molecular Clouds

Somewhere around 10-50% of the hydrogen in our Galaxy is in molecular clouds.

Composition of clouds:
- 75% molecular hydrogen (H2)
- 24% Helium
- 1% heavier elements and dust

Masses of clouds: a few solar masses to 1 million solar masses

Density: 100 to $10^6$ hydrogen molecules per cubic centimeter (Earth's atmosphere has $2.5 \times 10^{19}$ $N_2$ and $O_2$ molecules per cubic centimeter)

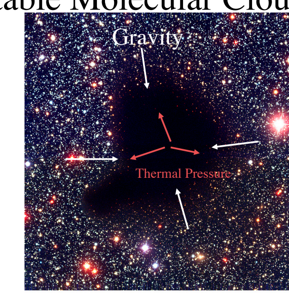
Temperature in cloud: < 50 kelvin

Interior of clouds are shielded from UV radiation by dust grains. Clouds are opaque to light.

All stars are thought to form in molecular clouds.

# Steps of Star Formation I: Formation of Cold, Unstable Molecular Clouds


Low density gas (1 atom per cc) is swept up into cold dark molecular clouds. Gas in clouds is cold (10-50 K) and dense (100-$10^6$ hydrogen molecules per cc)




Pre-Collapse Black Cloud B68 (visual view)
(VLT ANTU + FORS 1)

ESO PR Photo 02a/01 (10 January 2001) © European Southern Observatory

Cold dense gas may be initially in equilibrium. However, if the cloud is massive and cold enough, a small perturbation may cause it to collapse. Collapse probably happens within 100,000 years.

## Gravity and Thermal Pressure in Clouds of Gas

Pre-Collapse Black Cloud B68 (visual view)
(VLT ANTU + FORS 1)

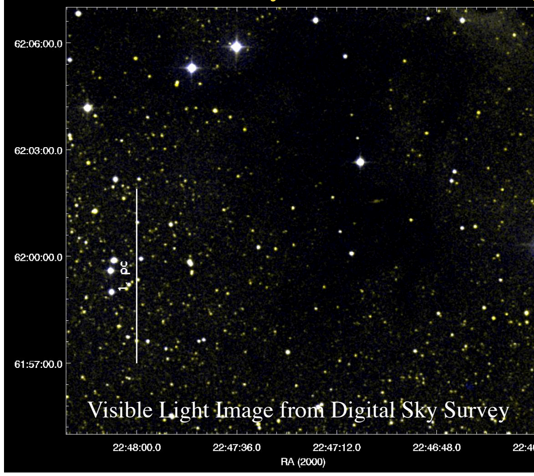


Consider a self gravitating cloud of gas which is slightly perturbed (compressed). Thermal and gravitational energy equal, so cloud neither contracts nor expands.

If gravitational energy decreases faster than thermal energy increases, graviational energy overwhelms thermal pressure and cloud collapses.

Jeans mass [solar masses] = 3.7 x $(\text{Temp}/10\text{K})^{3/2}$ x $(n_{H2}/10^4\ \text{cm-3})^{1/2}$

## The Dark Clouds Lynds 1211 in Visible Light



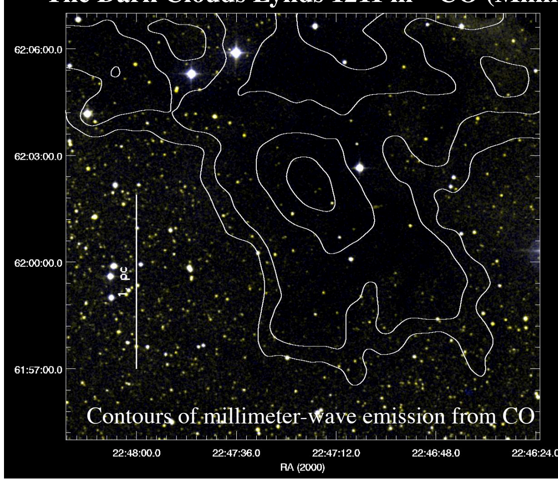

Stars form in cold clouds opaque to visible light.

Temperature: 18-50 K (293 K room temperature)

Composition: molecular hydrogen, trace components of dust, CO, ..

Density: 100-100,000 per cubic cm (100,000,000 less than Earth's atmosphere)

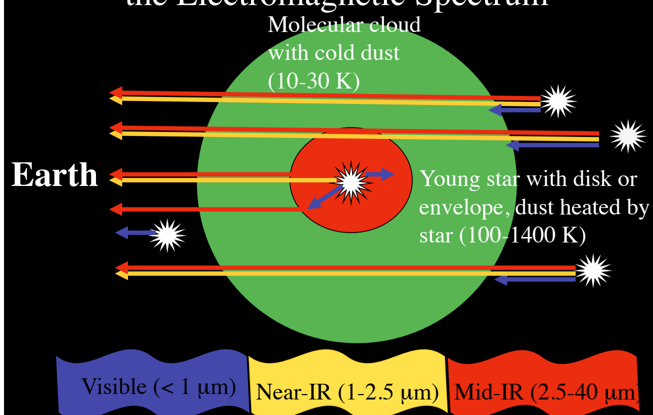
## The Dark Clouds Lynds 1211 in $^{13}$CO (Millimeter)




Molecular clouds can be mapped through observations of CO and other molecules

Contours: $^{13}$CO (1-0) (3 mm) observed at Five College Radio Astro. Observatory

## The Infrared Astronomer's View of the Electromagnetic Spectrum



## The Dark Clouds Lynds 1211 in $^{13}$CO (Millimeter)

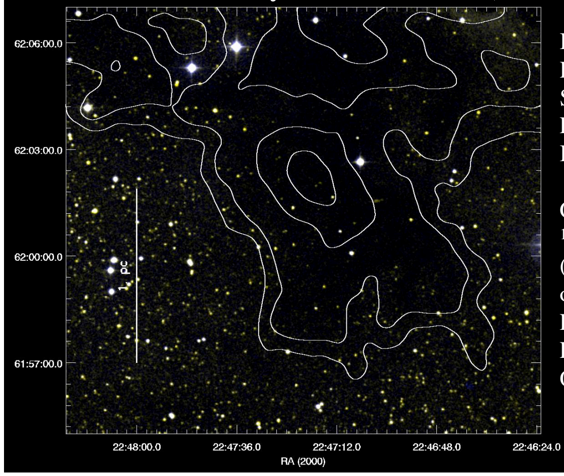



Image: Digital Sky Survey Red and Blue Images

Contours: $^{13}$CO (1-0) (3 mm) observed at Five College Radio Astro. Observatory

## The Dark Clouds Lynds 1211 from Spitzer

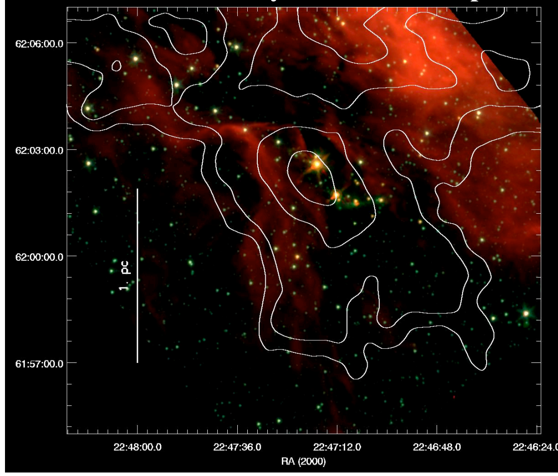
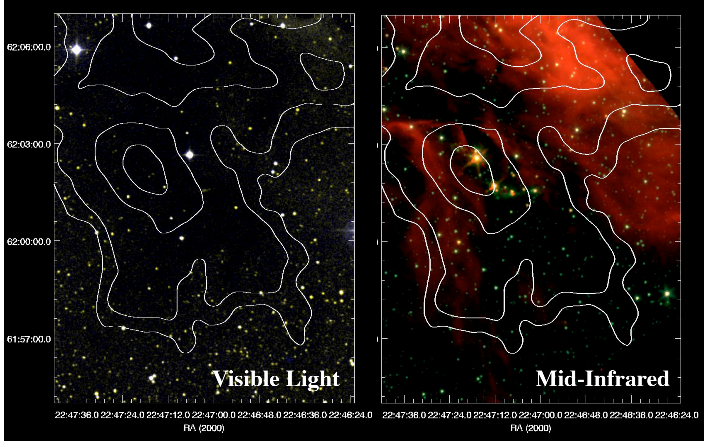


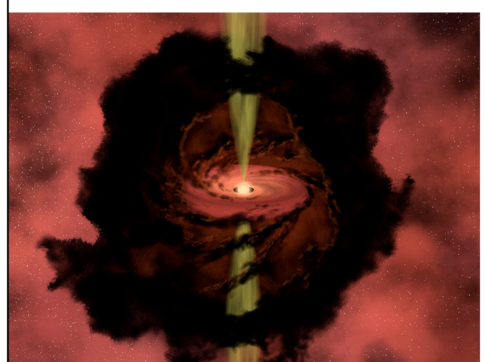

Image: Spitzer/IRAC
3.6μm
4.5μm
8μm

Contours: $^{13}$CO emission measured at 3 mm

## Young Stars in The Dark Clouds Lynds 1211




## Protostars



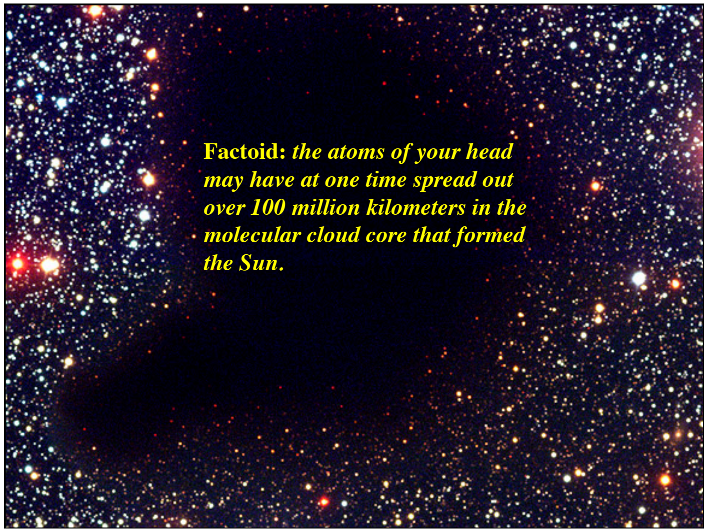
Stars form in dense, self gravitating parts of molecular clouds called molecular cores.

Densities $10^4$ molecular hydrogen per cubic centimeter.

Gas in core begins to collapse. Center of core collapses first, forming a small protostars.

Gas continues to rain down on protostar, and the protostar grown in mass.

Due to conservation of angular momentum, much of the mass ends up on a disk of gas.




# Angular Momentum

Angular momentum must be conserved as cloud collapses.

Goes from size of 3.5 pc for 1 Hydrogen per cc (11.5 light years)

To size of 0.13 pc for $10^4$ $H_2$ (hydrogen molecule) per cc (0.42 parsecs)

To size of primordial sun $10^{10}$ centimeters

Thus size deceases a nine orders of magnitude ($10^9$)

Angular momentum = mass x 2 $\pi$ / rotation period x radius$^2$

Conservation of angular momentum implies rotational period increases by $10^{18}$

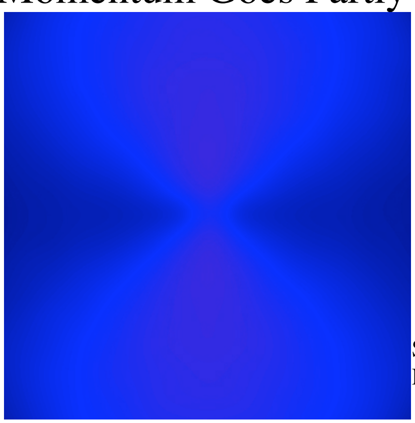
If initial rotation rate is once per 200 million years

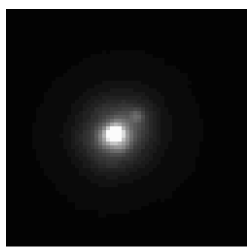
The rotation rate of the Sun would then be 1 per second.

Where does it go?

**Some goes into disk, some is lost through winds and jets. The disk, and thus planets, are the result of the conservation of angular momentum.**

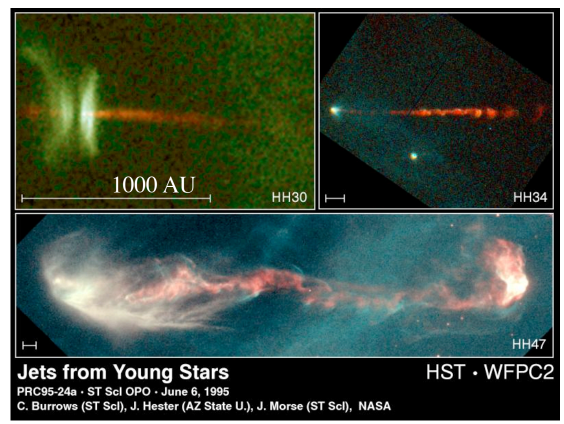
# In Binary Stars, the Angular Momentum Goes Partly into the Orbit



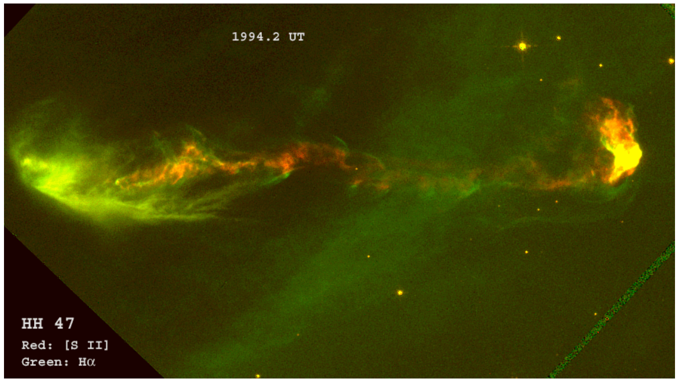


Simulation: Matthew Bate

# For Single Stars, the Angular Momentum Goes into the Disks and Jets



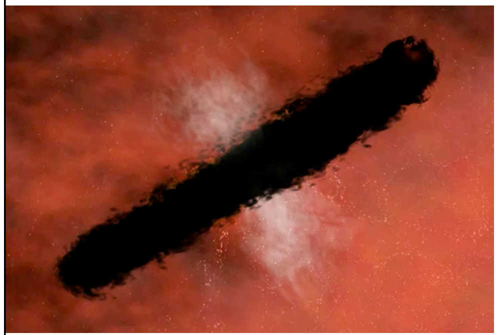
## Jets from Protostars




Jets of gas moving at 100 $kms^{-1}$ from star. Hits ambient gas and heats up to high temperatures (10,000 K). The hot gas glows.

Jets may help remove angular moment from protostar.

## Pre-Main Sequence Evolution



Once the envelope is gone, the star has accreted most of its mass.

At this point, the energy of a young stars like our Sun will come primarily from the slow contraction of the star.

As the star contracts, gravitational energy is converted into thermal energy.

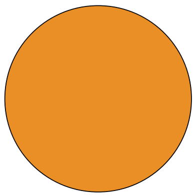
Thermal energy radiated into space.

Young pre-main sequence often are surrounded by disks of dust and gas.

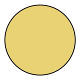
Often show high amounts of stellar activity (stellar flares).

**Baby Stars are BIG**

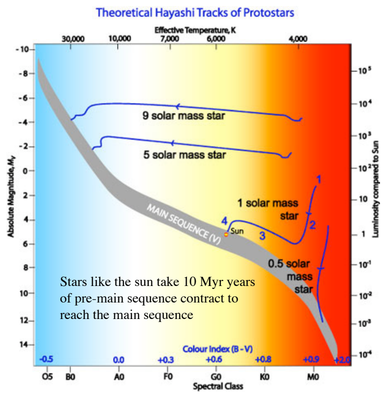
The Sun 4.6 Billion years ago



The Sun Now



## Pre-Main Sequence Evolution




The cores of the pre-main sequence stars do not have the density and temperature necessary for gravitational contraction.

$L = 4\pi R^2 \sigma T^4$
R = radius of star
σ = Stefan-Boltzman constant
T = temperature of star

Stars initially follow Hayashi track (named after Japanese astronomer Chushiro Hayashi)

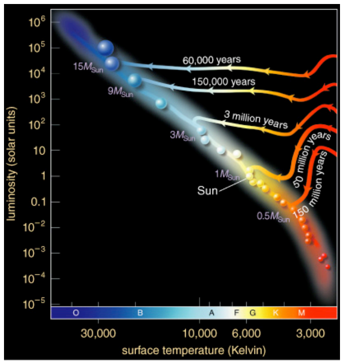
As they radiation, they lose gravitational energy and shrink. The resulting change in energy is:

$\Delta E = GM^2 \Delta R/R^2$

Which is radiated into space

$DR/DT = 4\pi R^4 \sigma T^4/GM^2$

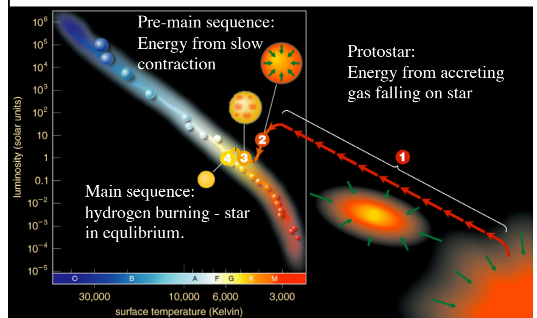
## Pre-main sequence evolution and the descent to the main sequence




The amount of time a star spends in pre-main sequence contraction before it reaches the main sequence depends on its mass.

Our sun spent roughly 50 million years to get the main sequence. A star half the mass of our sun takes 150 million year. An object with mass < 0.08 solar masses never reaches the main sequence and continues to contract.

## Where does the energy come from?




Luminosity =

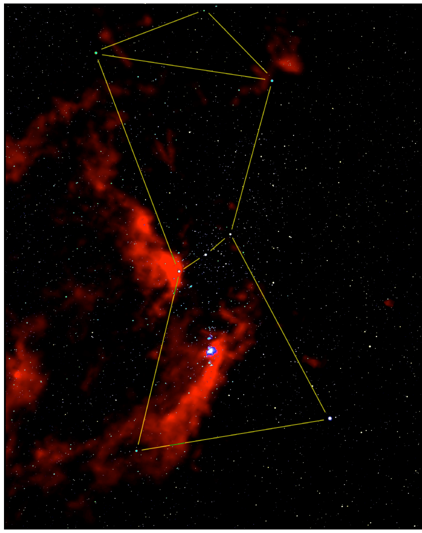
For protostars:

G M (ΔM/Δt)/R

For pre-main sequence stars:

$G M^2 (DR/Dt)/R^2$

Mass of star = M
Radius of star = R
Change in mass per unit time = ΔM/Δt
Change in radius per unit time = ΔR/Δt

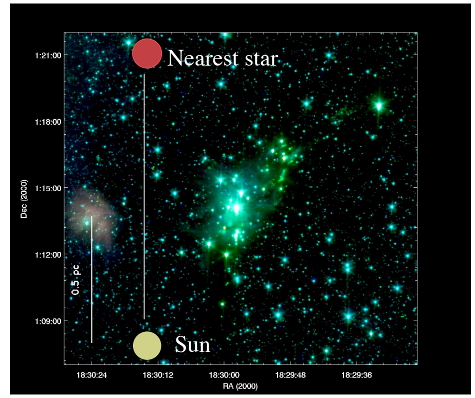
# Giant Molecular Clouds

Not all clouds are small little globules (like B68)

Most stars form in giant molecular clouds with masses around 1 million solar masses and lengths of 150 pc (500 light years)

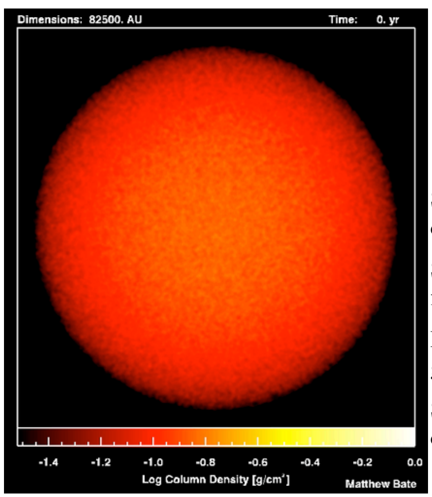
One of the nearest such clouds is found in Orion

# Star Formation in Clusters




Most stars do not form alone in small molecular globules like B68, but in clusters within giant molecular clouds.

These embedded clusters contain 100-1000 stars in regions a few light years across.




# Numerical Simulation of Star Cluster Formation in a Turbulent Cloud

Supersonic turbulence creates shocks

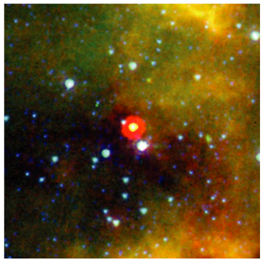
Shocks create high density filaments

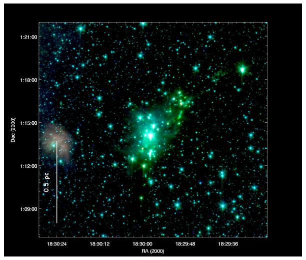
Filaments collapse due to gravity

Stars form, grow and compete for gas

## Numerical Simulation of Star Cluster Formation in a Turbulent Cloud

## Cluster or Isolation?

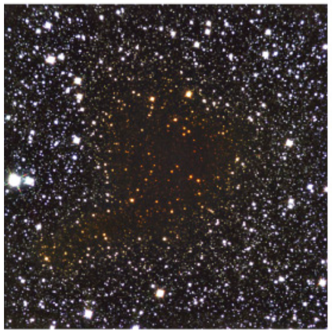




Where are most stars form: in isolation or in clusters?

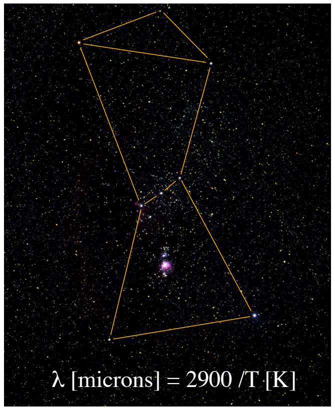
## Infrared Observations of Star Formation: Penetrating the Dust

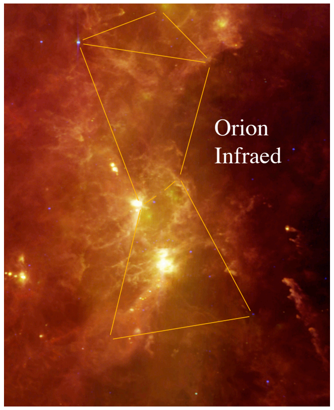
Visible Light



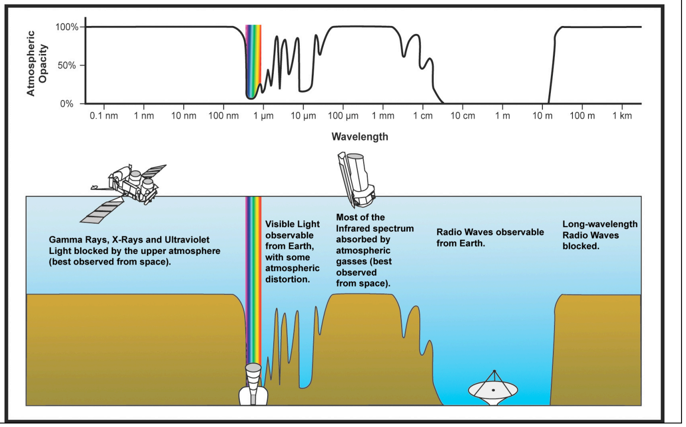
Infrared Light

## Infrared Observations of Star Formation: Detecting Emission from Hot Dust

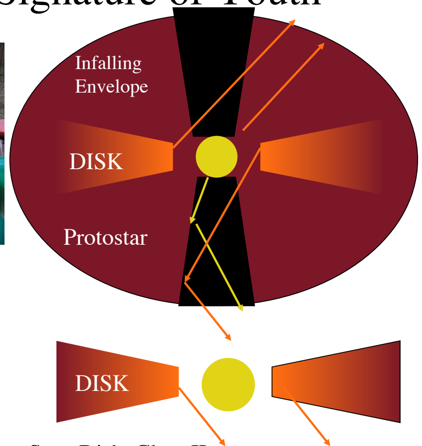



## Infrared Astronomy from Space



## Dust as a Signature of Youth

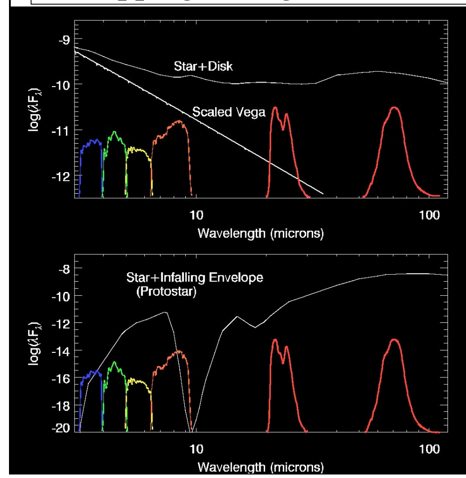



Star+Disk, Class II

Emission from dusty disks and envelopes easily detected in the IRAC & MIPS mid-IR bands.

This emission can be used to identify and classify young stars -

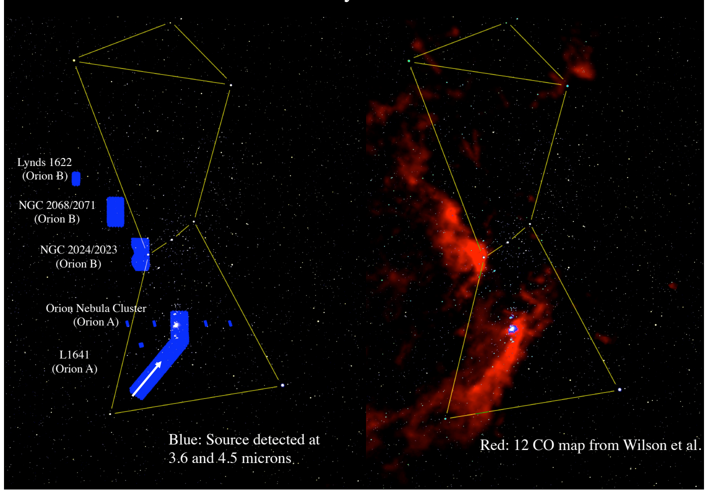
## Mapping Young Clusters: Infrared Excess



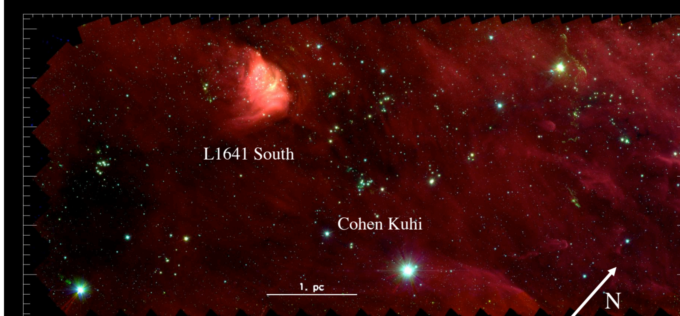

Disk models from D'Alessio et al. 2004

Protostar models generated using method of Kenyon, Calvet & Hartmann (1993)

## The IRAC Survey of Orion A & B



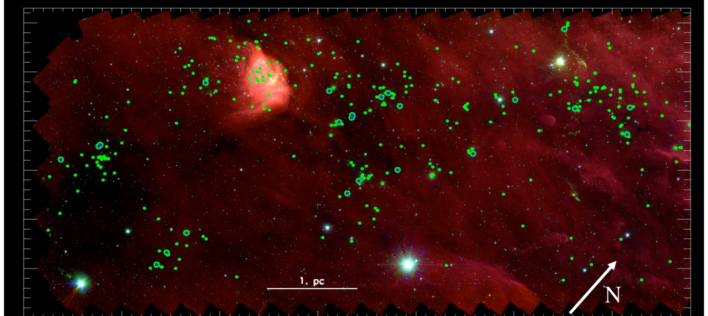

## L1641 Cloud Images




Red: 8 micron Green: 4.5 micron Blue:3.6 micron

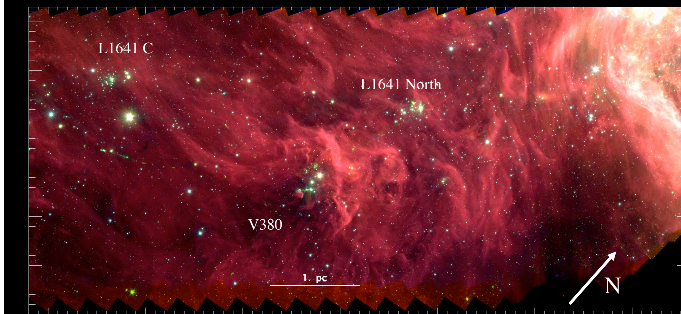
# L1641 Cloud Images

Small Green Circles: IR-ex sources, Big Green/Blue Circles: IRAC selected Protostars




**Red: 8 micron  Green: 4.5 micron  Blue:3.6 micron**

# L1641 Cloud Images

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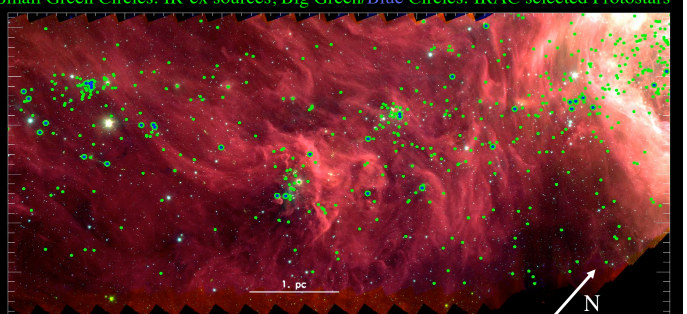
# L1641 Cloud Images

Small Green Circles: IR-ex sources, Big Green/Blue Circles: IRAC selected Protostars

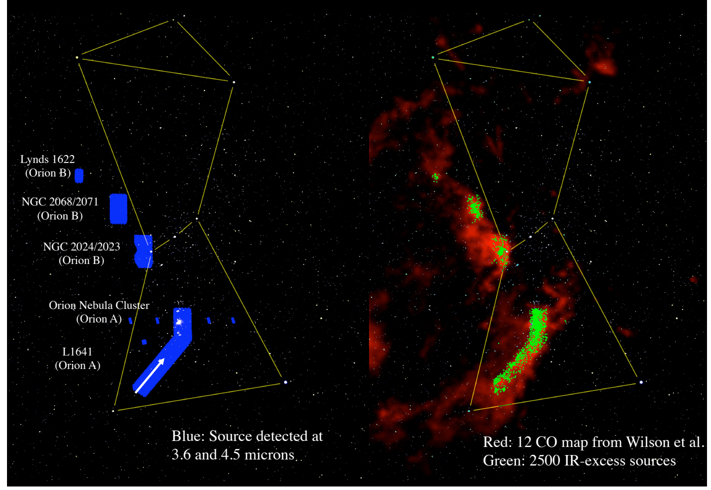



**Red: 8 micron  Green: 4.5 micron  Blue:3.6 micron**

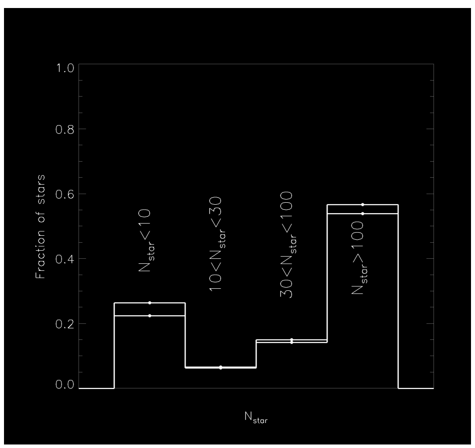
# The Orion Nebula Cluster

# The Orion Nebula Cluster


## The IRAC Survey of Orion A & B



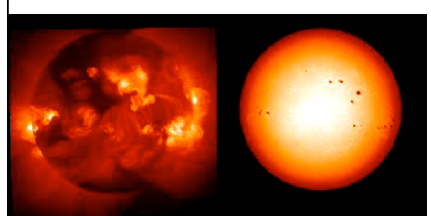

## The Distributed Population in GMCs




About 25% of the stars are found in relative isolation

Caveat: This may only be valid for the nearest 1 kpc.

Super-star clusters with >10,000 stars may be an important component at greater distances.



# X-ray Emission from Young Stars

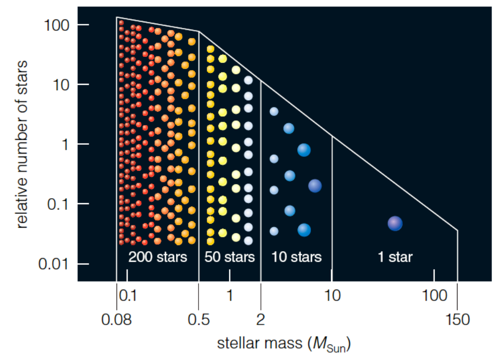
The Sun emits around 1/100,000 of its luminosity at X-ray wavelengths.

Young stars can emit 1/1000 to 1/100 of their luminosity at X-rays.

## X-ray Images of the Orion Nebula

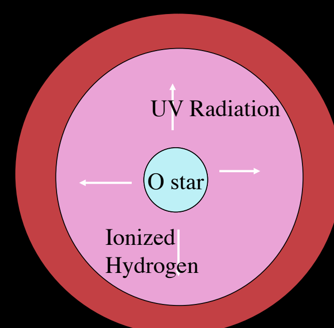
Data from Chandra X-ray observatory, COUP project, Ettore Flaccomio

## The Initial Mass Function





## HII Regions




UV radiation from hot stars can ionize hydrogen atoms in the surrounding cloud.

The ionized Hydrogen is referred to as HII

Neutral hydrogen: HI
Ionized hydrogen: HII

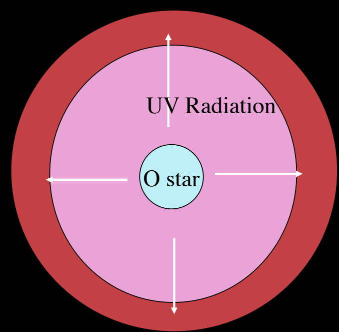
H + UV -> $p^+ + e^-$ Ionization

$p^+ + e^-$ -> H Recombination

An equilibrium is reach where the number of ionizations equal the number of recombinations.

All UV radiation with wavelengths of $\lambda < 912$ Angstroms or $\lambda < 0.0912$ Microns is absorbed.

## Polcyclic Aromatic Hydrocarbons



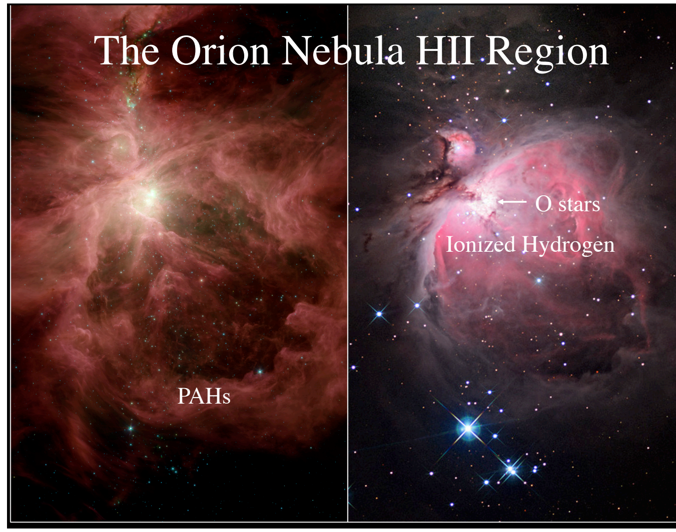

The UV radiation with

λ> 912 Angstroms

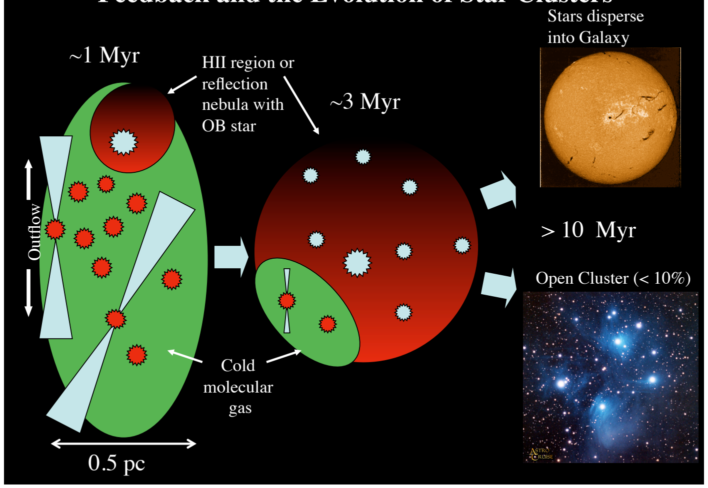
can escape the HII region and heat the surrounding cloud. The cloud has hydrocarbon molecules called Polycyclic Aromatic Hydrocarbons or PAHs.

The PAHs absorb the UV radiation and glow in the infrared

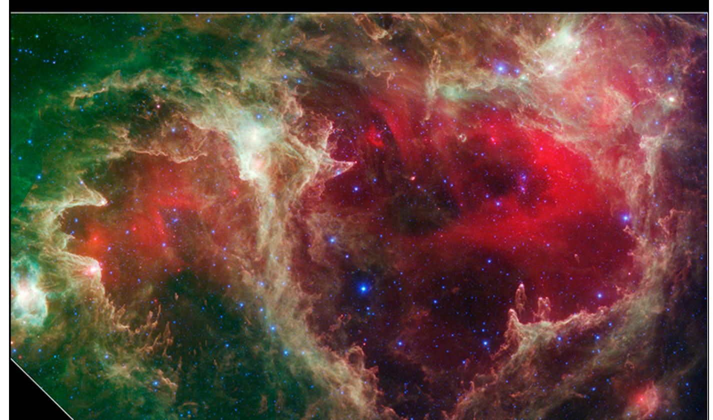
## The Orion Nebula HII Region

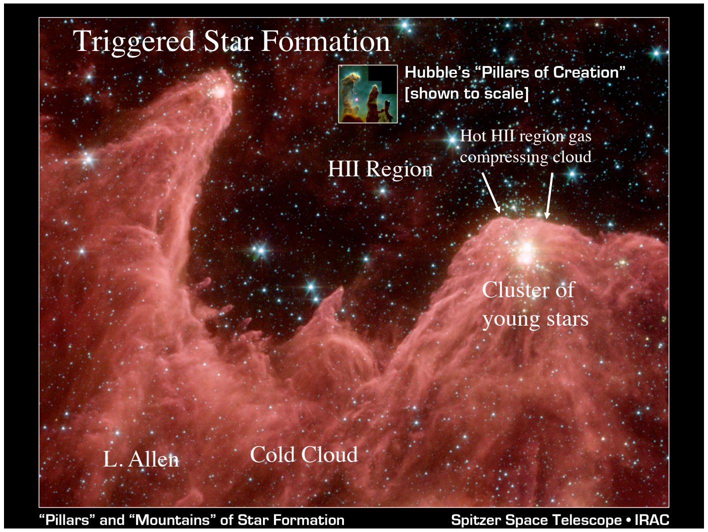



## Feedback and the Evolution of Star Clusters

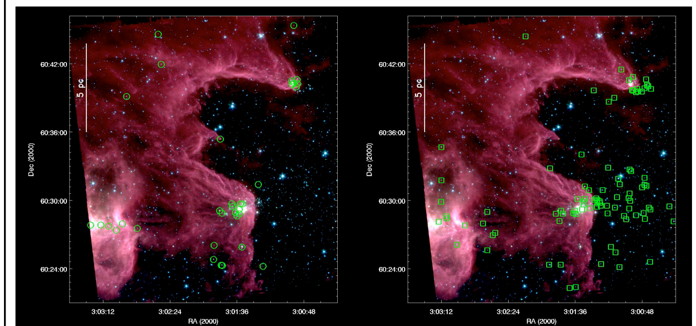



## The W5 HII Region





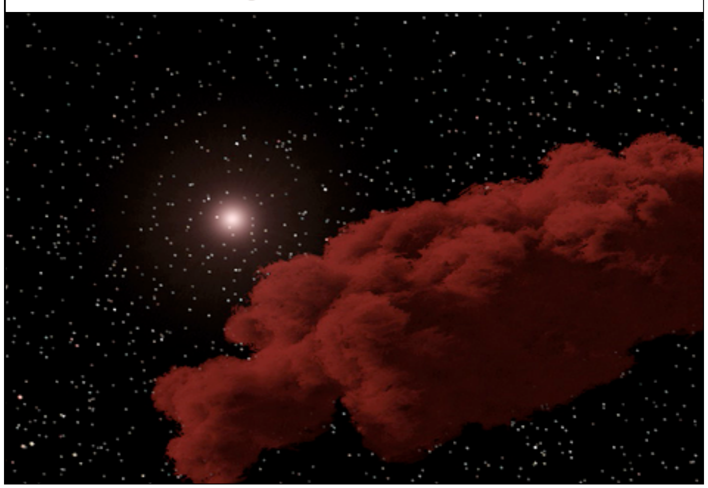

# Triggered Star Formation




Protostars

Pre-main sequence stars

## 4.6 Billion Years Ago: The Birth of our Sun?



# Star Formation Review

What is a molecular cloud?

What are the stages of star formation and how long do the last?

What is a protostar and what is a pre-main sequence star?

Why is angular momentum important?

What is a jet?

Do stars form in clusters or isolation?

Why is the infrared important for studying star formation?

How do we detect disks around stars in the infrared?

How is star formation terminated in clouds?

What is triggered star formation?