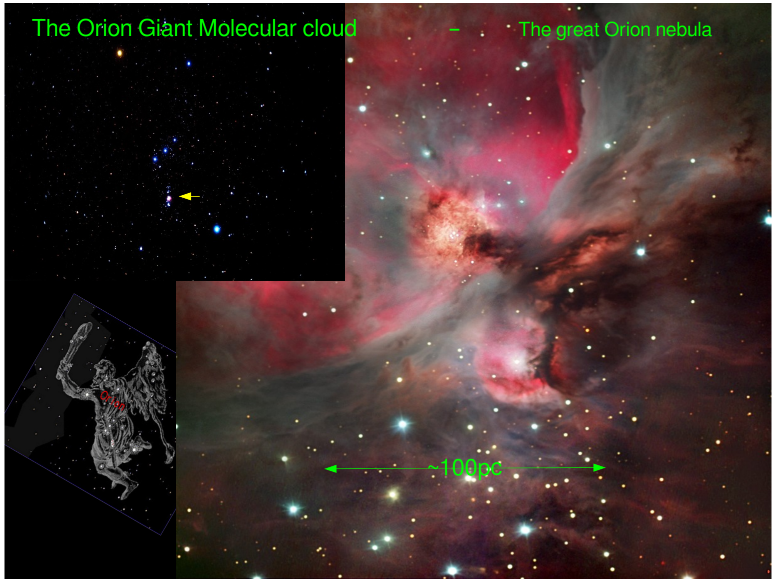
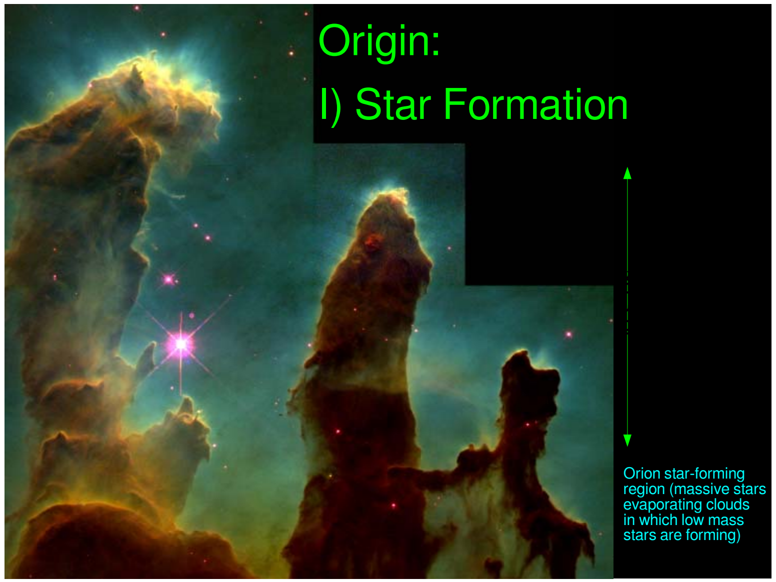
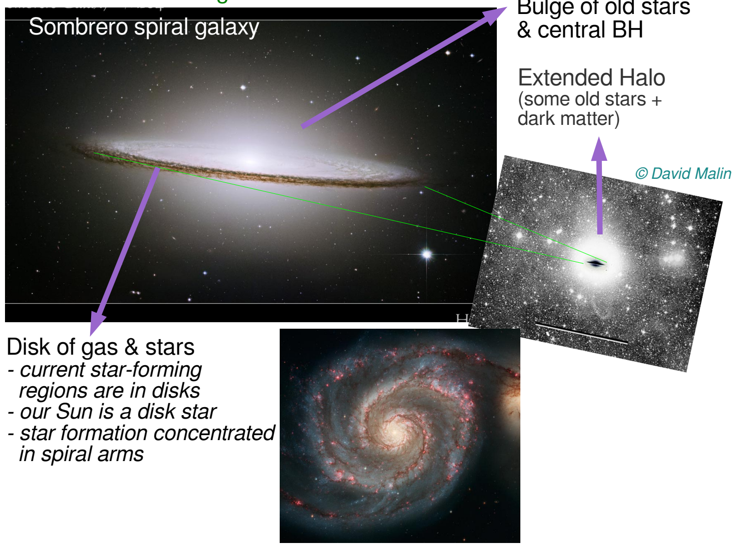


the Horse-head nebula in Orion

a B-star inside (strong UV source)



Where are stars forming?



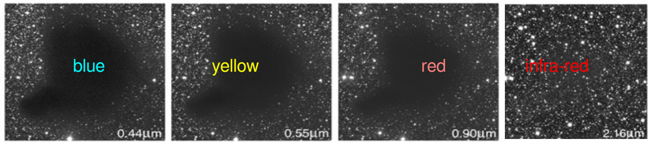
How much raw material in the Milky Way (10^{10} years old, ~ 10^{12} $M_\odot$):

dark matter:	~90% (~10^{12} $M_\odot$)	
stars:	~10% (~10^{11} $M_\odot$)	(central black hole: ~3×10^6 $M_\odot$)
interstellar medium:	~1% (~10^{10} $M_\odot$)	= gas (mostly) +dust (~1%)

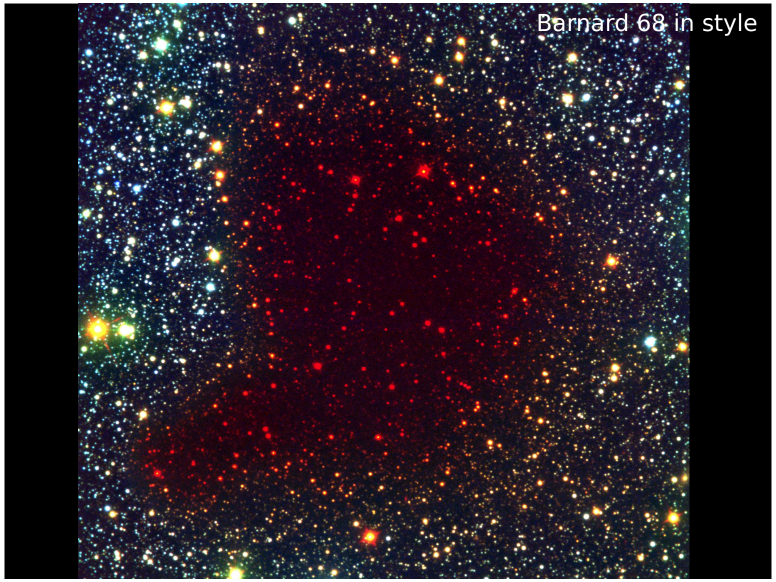
Interstellar medium: not a smooth continuum,
- punctuated by clouds & cavities
- regions of very cold (~ 10K), cold (~100K), warm (10^4 K) and very hot (~10^6K)
  as affected by nearby stars (stellar wind, supernova,outflow...)
  pressure dominated, in turn, by molecular, atomic, partly ionised & fully ionised gas
- average interstellar medium number density ~1 cm^{-3} best vacuum on Earth: n~10^3 cm^{-3}

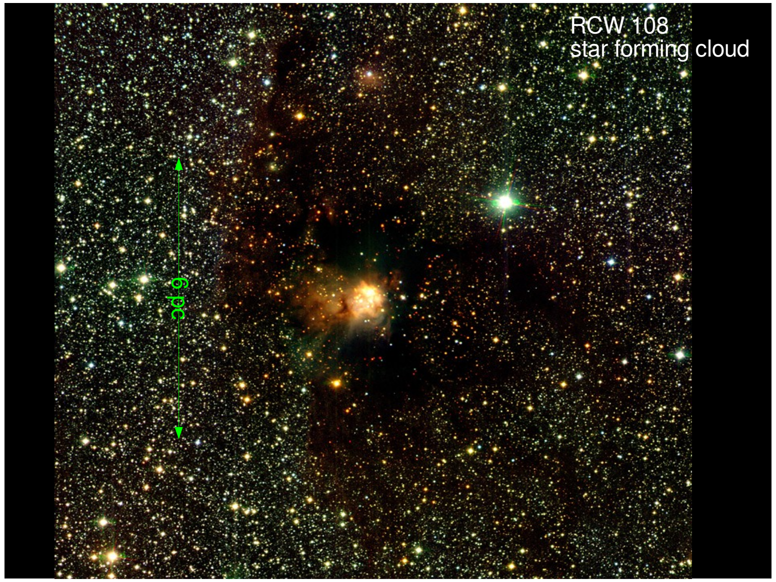
Of relevance to star formation: giant molecular clouds, Bok globules

Giant molecular cloud:	~50pc	~10^5 $M_\odot$	~10^2 cm^{-3}	Sun: ~10^{-8} pc
(dense core of GMC:	~1pc	~100 $M_\odot$	~10^8 cm^{-3})	n ~ 10^{26} cm^{-3}
Bok globules:	~1pc	~10 $M_\odot$	~10^6 cm^{-3}	(ignoring factors of 3,π...)



Dark Cloud Barnard 68 Rayleigh scattering of star light (ext. in V of ~35 mag)





Stars form by gravitational collapse

A necessary condition for gravitational collapse

The Jeans criterion (1877-1946)

Stable, gravitational bound system satisfies the virial theorem $E_{kin} + \frac{1}{2}E_{pot} = 0$

The cloud will collapse only if $E_{kin} + \frac{1}{2}E_{pot} < 0$

Assume a spherical, constant-density, constant-temperature cloud:

$$E_{pot} = -\frac{3}{5}\frac{GM^2}{R}, \qquad E_{kin} = \frac{3}{2}NkT = \frac{3}{2}\frac{M}{\mu m_H}kT$$

$$E_{kin} < -\frac{E_{pot}}{2} \rightarrow M > M_J = \left(\frac{5kT}{G\mu m_H}\right)^{3/2}\left(\frac{3}{4\pi\rho}\right)^{\frac{1}{2}}$$

Knowing the temperature & density of a cloud, we know the minimum mass it has to have in order to collapse under its own weight.

Diffuse hydrogen cloud:	T ~ 50K,	n ~ 500 cm^{-3}	---> M_J ~ 1500 $M_\odot$
(typically < 10^2 $M_\odot$)			
GMC dense core:	T ~ 150K,	n ~ 10^8 cm^{-3}	---> M_J ~ 17 $M_\odot$
(typically 10^2 $M_\odot$)			
Barnard 68 Dark cloud:	T ~ 10K,	n ~ 10^6 cm^{-3}	---> M_J ~ 3 $M_\odot$
(~ 3 $M_\odot$)			

What happens during the collapse to stars?

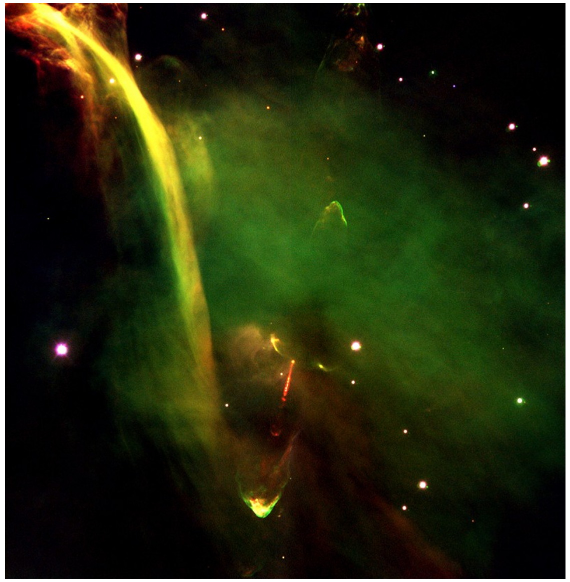
1) stage A: free-fall (dynamical timescale)
   gravity overcomes the pressure support
   nearly free-fall collapse, $t \sim t_{dyn} \sim (G\rho)^{-1/2} \sim 10^3$ yr for dense core of GMC
      center of the cloud higher density --> collapse faster --> central cusp
   temperature of the cloud remains ~ constant (isothermal)
      gravitational energy release is lost to the outside
   this is possible as long as the cloud is still transparent to its own radiation

   fragmentation occurs due to decreasing Jeans mass $M_J \propto T^{3/2} \rho^{-1/2}$

2) stage B: pre-main-sequence (thermal timescale)
   further contraction -- cloud becomes optically thick (heat not lost instantly)
   free-fall and fragmentation stop, contracts slowly as heat diffuses out,
   $t_{KH} \sim E/L \sim 10^7$ yr for 1 $M_\odot$, takes longer (shorter) for a lower (higher) mass star
   strong stellar wind ($\sim 10^{-8}$ $M_\odot$/yr);
   high angular momentum material: forming into a disk
      viscosity in the disk moves material inward, shooting jets
      stellar UV photons and winds disperses disk/cloud

3) stage C: main-sequence stars (nuclear timescale)
   central temperature so hot that H burning starts, $t \sim t_{nuc} \sim Mc^2/L$

Jets and winds from forming stars in Orion



Star formation has a propensity for forming low-mass stars

The final stellar mass is not the initial M_J

1) fragmentation
   Isothermal collapse phase, T constant, ρ increases ---> M_J decreases
   An initially collapsing cloud can fragment ---> lighter stars
   Fragmentation stops when isothermal phase stops

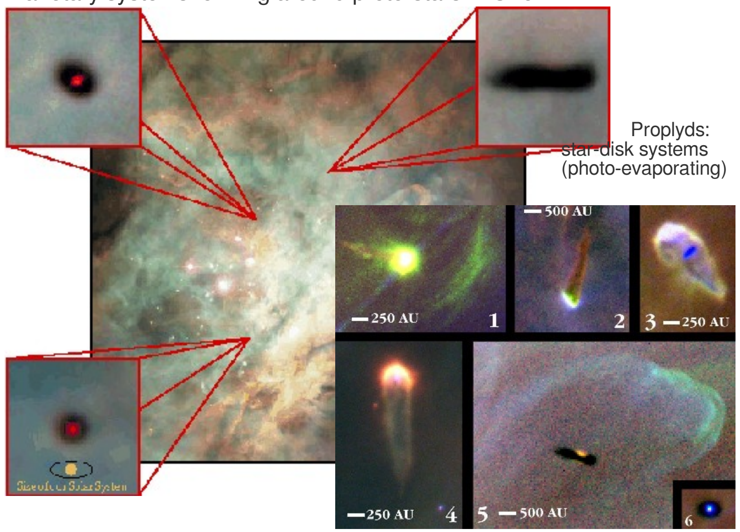
2) angular momentum issue
   d ~ 1 pc --> d ~ 10^{-8} pc
   --> forming binary stars, triple stars....

3) observed:
   20 times as many stars < 1 $M_\odot$ than > 1 $M_\odot$ (to 0.1 $M_\odot$)
   Average mass of a star ~ 0.3 $M_\odot$

   the Salpeter initial mass function for more massive stars: (IMF)

   Number of stars dN inside a mass bin $(M, M+dM)$: $\frac{dN}{dM} \propto M^{-2.35}$

Planetary systems forming around proto-stars in Orion

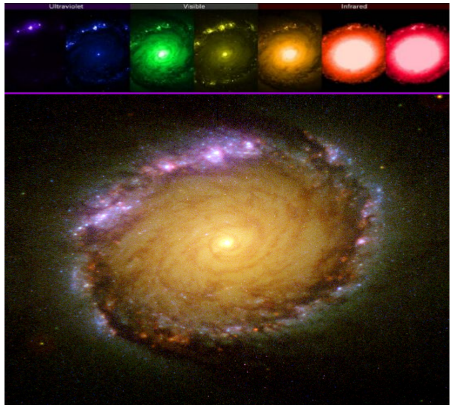


Proplyds:
star-disk systems
(photo-evaporating)

The Milky Way galaxy

- is forming stars at a rate of ~1 $M_\odot$/yr
- each star takes ~10^6 yr to mature into a main-sequence star
- does not mean star formation will last only another 10^9 years --- "recycling"

Some galaxies form stars at a much higher rates - star-burst galaxy (> 100 $M_\odot$/yr)



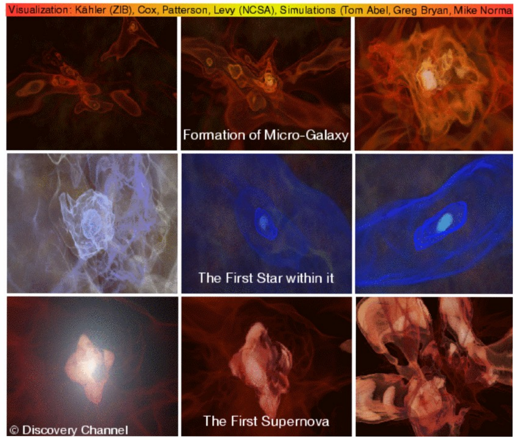
massive, short-lived stars are bluer
less massive, old stars are redder

blue region: recent star formation

NGC 1512: star-burst ring
galaxy-galaxy collision?

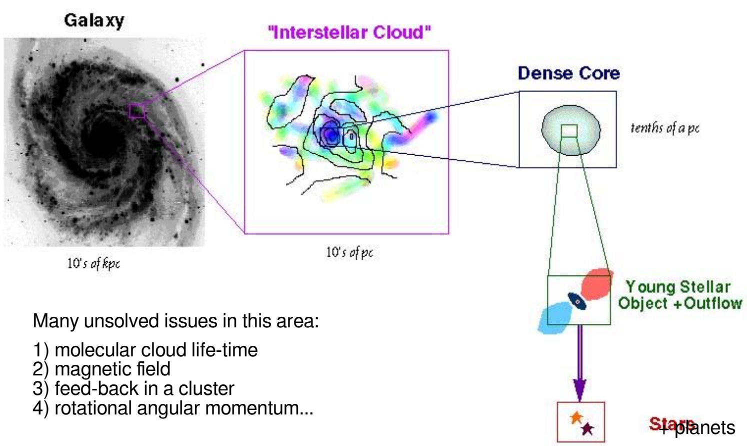
The first star in the Universe

- oldest stars found are in the globular clusters (~13 Gyr), 2nd generation?
- first generation of stars may have been much more massive (cooling by molecular hydrogen, not as efficient); if so, they would have long since gone.



Courtesy A. Goodman

Star Formation in the Interstellar Medium



Many unsolved issues in this area:

1) molecular cloud life-time
2) magnetic field
3) feed-back in a cluster
4) rotational angular momentum...