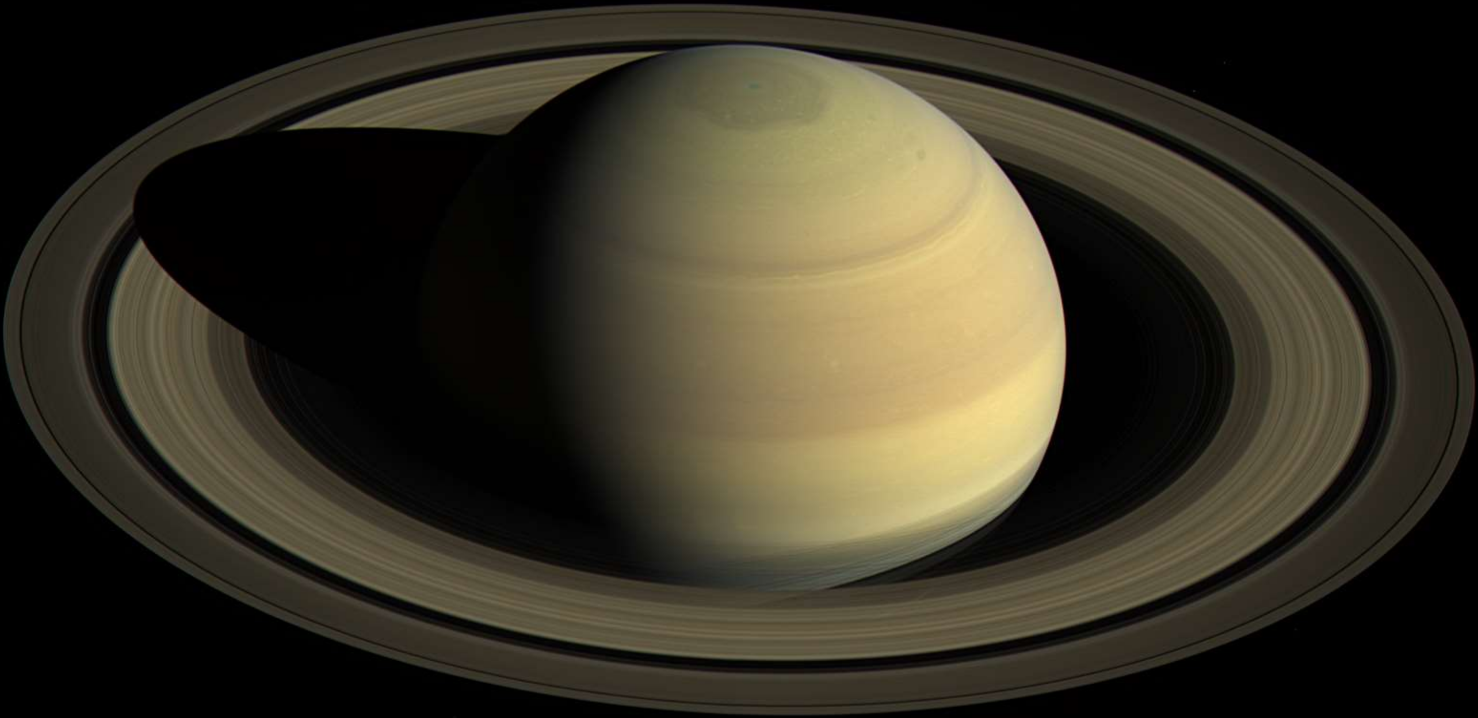
AST 2002
Introduction to Astronomy



A Few Quick Things…

E-mailing me: Must have AST2002 in the subject

Mary Hinkle, Graduate Teaching Assistant:

Office Hours: Mon 1:30-3:00pm. PSB 316

My office hours: Mon 3:00-4:00pm. PSB 308

Tue 3-4 pm. PSB 308

Curved Exam Grades have been Uploaded to Webcourses… this should give a reasonable idea how you are doing in the class… am still uploading extra credit

Scores on Webcourses will not be accurate until near the end of the course. Sorry.

LAST Knights Under the Stars Event – Thursday 19th April

Opportunity to make up the 1% extra credit that was offered (if you haven't been yet, worth 2%) ***– Last chance for extra credit..***

What have we covered?

Chapter 12: Surveying the Stars

12.1. Properties of Stars

- How do we measure stellar luminosities?
- How do we measure stellar temperatures?
- How do we measure stellar masses?

12.2. Patterns Among Stars

- What is the Hertzsprung-Russel diagram?
- What is the significance of the main sequence?
- What are giants, supergiants, and white dwarfs?

12.3. Star Clusters

- What are the two types of star clusters?
- How doe we measure the age of star clusters?

Stellar Diversity

Hubble Space Telescope image of Baede's window towards the galactic center…

Some stars are:

Blue…
White…
Yellow…
Red…

Some stars are:

Really bright…
Much dimmer…

Are there more:

- *blue or red stars?*
- *Brighter or dimmer stars?*

Any dim blue stars?

Binary Systems and Stellar Masses

If you remember (from Newton's formulation of Kepler's 3rd law), binary systems allow us a method to determine the mass. From the relationship for circular orbits, $v = 2\pi r / p$, *we need two of the following:*

1. Orbital period (p)
2. Orbital separation (a or r = radius)
3. Orbital velocity (v)

→ Fortunately, approximately half of all stars are in binary systems.

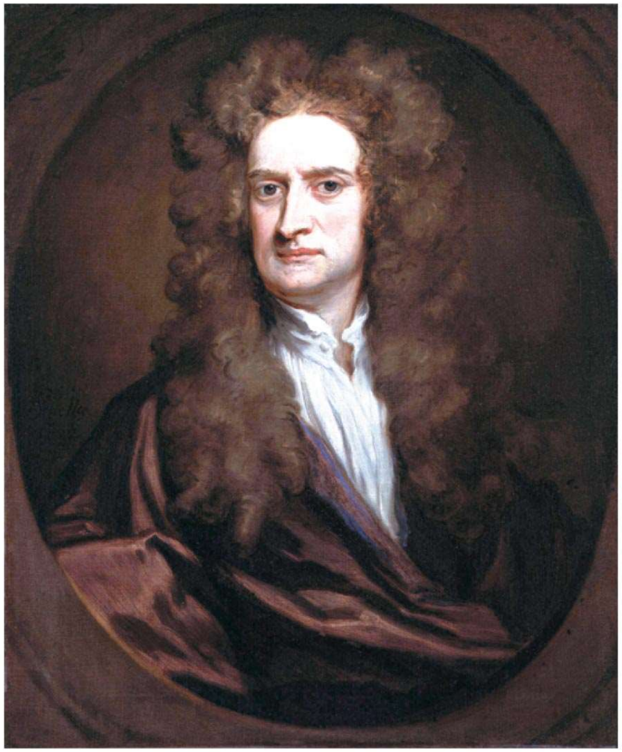
How can we determine these properties?

- Transits…
- Doppler Shifts…
- Astrometry…

i.e. using the same techniques used for detecting exoplanets

Determination of Mass in Binary Systems

http://www.austincc.edu/jheath/Solar/Hand/NVK3L/nvk3l.htm



Isaac Newton

We measure mass using gravity, and Newton's version of Kepler's 3rd law:

$$p^2 = \frac{4\pi^2}{G(M_1 + M_2)} a^3$$

p = period

a = average separation

G = Universal Gravitational Constant (6.67408×10^{-11} m^3 kg^{-1} s^{-2})

M_1 and M_2 are the masses of the stars in the system

- Direct mass measurements are only possible for stars in binary star systems.
- But they can provide a framework for us to calculate the masses of other stars.

Example – Determining the Mass of a Binary System

From Kepler: $a^3 = p^2$or $\frac{a^3}{p^2} = 1$ where a = distance, p=orbital period

From Newton: $p^2 = \frac{4\pi^2}{G(M_1 + M_2)} a^3$

If we do calculations in terms of the mass of our Solar System (~M_{sun}), and use AU for distances we can make the equation a bit easier to handle:

$$\frac{a^3}{p^2} = M_1 + M_2$$

Example: A binary star system is found to have an orbital period of 2 years and an orbital separation of 4 AU.

Solution: Putting these into the equation we get: $\frac{4^3}{2^2} = \frac{64}{4} = 16\ldots$

→ We now know that $M_1 + M_2 = 16\ M_{sun}$

→ But that is as far as we can go. Or is it?

Relationship between Mass and Lifetime

Sun's life expectancy: 10 billion years

Until core hydrogen (10% of total) is used up

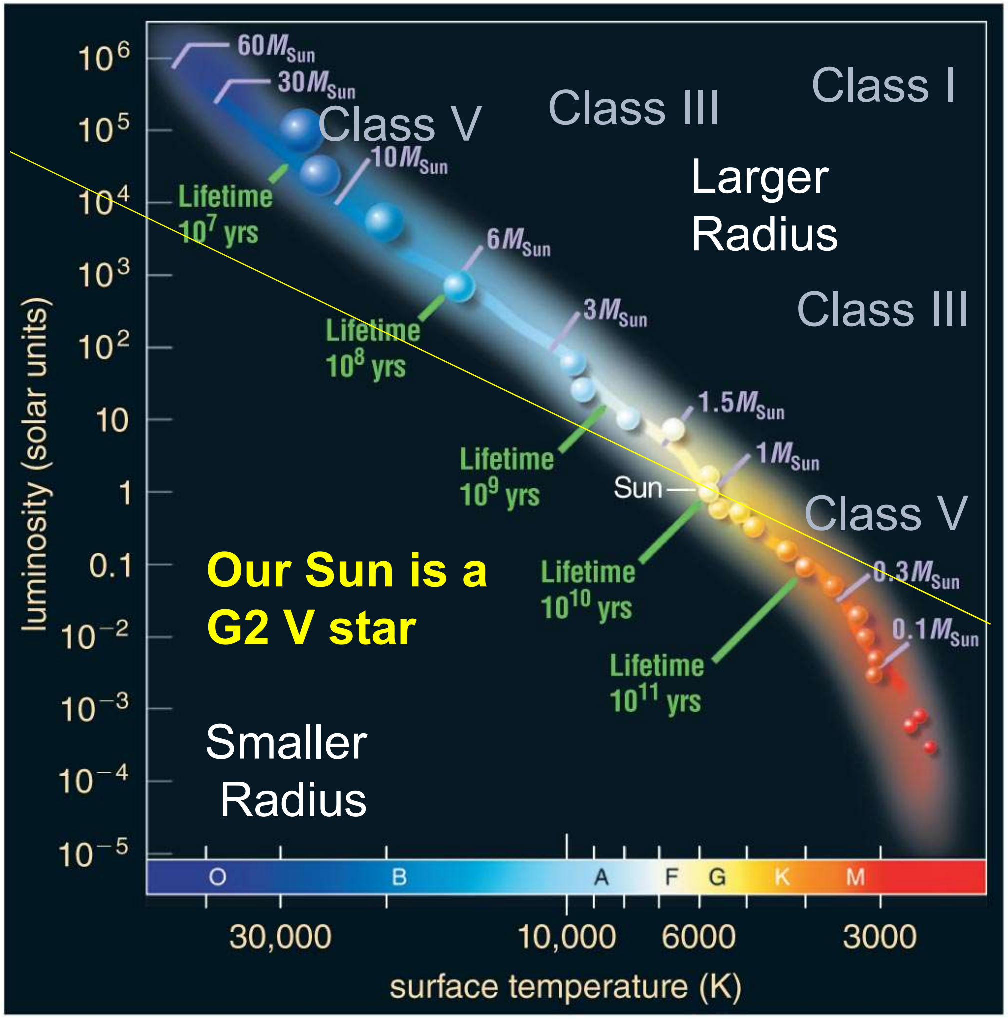
Life expectancy of a $10M_{Sun}$ star:

- 10 times as much fuel, BUT uses it 10^4 times as fast (10^4 L_{sun})
- 10 billion years × $10/10^4$ (=1000× shorter) = ~10 million years

Life expectancy of a $0.1M_{Sun}$ star:

- 0.1 times as much fuel, and uses it only 0.01 times as fast
- 10 billion years × 0.1/0.01 (= 100x longer) = ~100 billion years

Star Radii on the H-R diagram

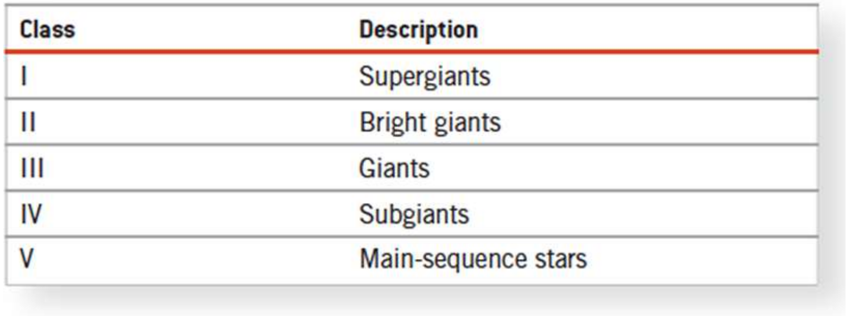


Larger Radius

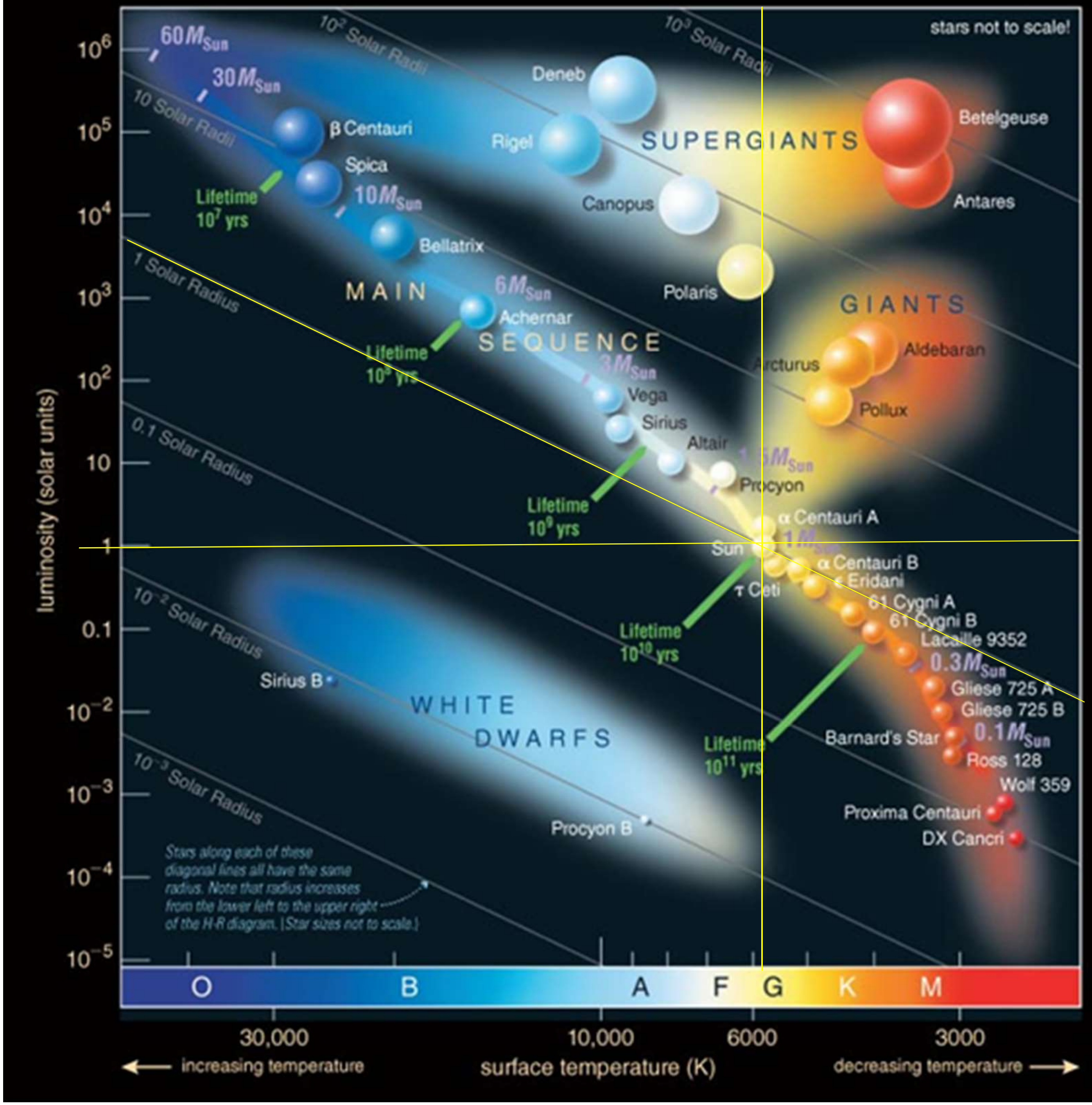
Our Sun is a G2 V star

Smaller Radius

- More massive main sequence stars will naturally be a little bit larger… (up to ~ $10R_{Sun}$)
- The only way for stars to become more luminous for a given temperature is if they are larger… (more surface area is irradiating heat)
- Class I supergiants ~1000 R_{sun}



Class	Description
I	Supergiants
II	Bright giants
III	Giants
IV	Subgiants
V	Main-sequence stars

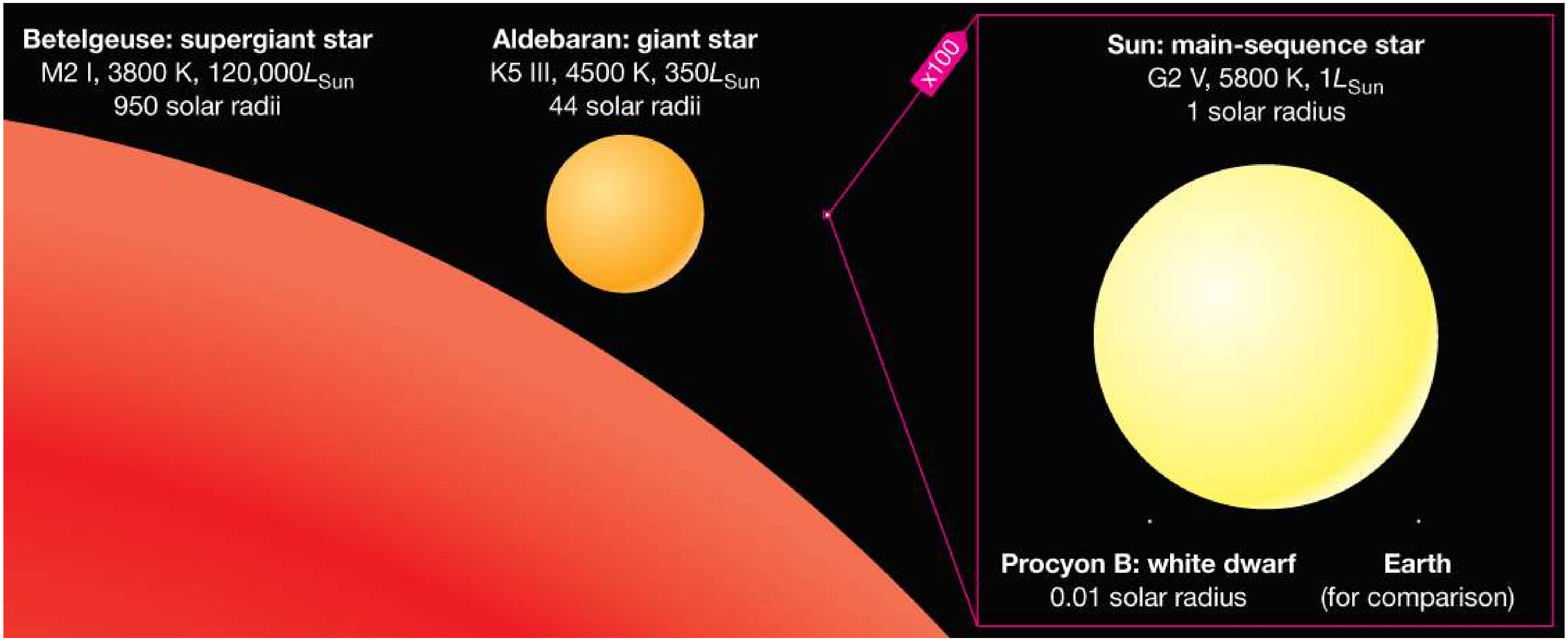


Now …

We understand:

- Mass-Luminosity relationship
- Main sequence
  - Masses
  - Lifetimes
- Sizes on Main sequence
- Giants & supergiants
- White dwarfs

Supergiants & White Dwarfs



- Giants & Supergiants are stars nearing the end of their lives
- At the end of the life of a low-mass star, the outer layers are ejected, and the “dead’ core remains – these are White Dwarfs

Two types of Star Clusters

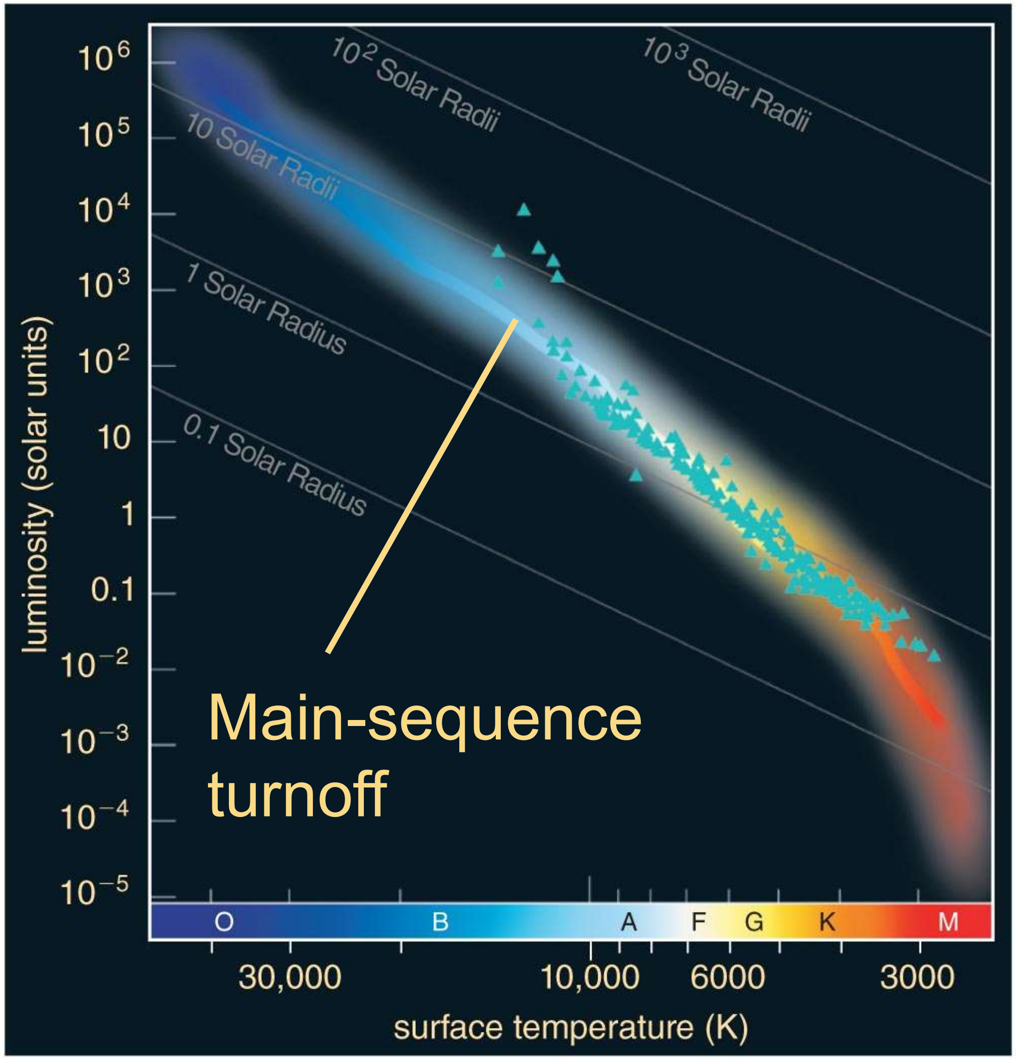
Open Cluster

- A few thousand loosely packed stars
- Young in age
- Located within the disk of the galaxy

Globular Cluster

- Up to millions of stars in dense ball, tightly bound by gravity
- Often much older in age
- Located in the halo region of the galaxy (above and below the disk)

How can we Determine the Age of a Star Cluster?

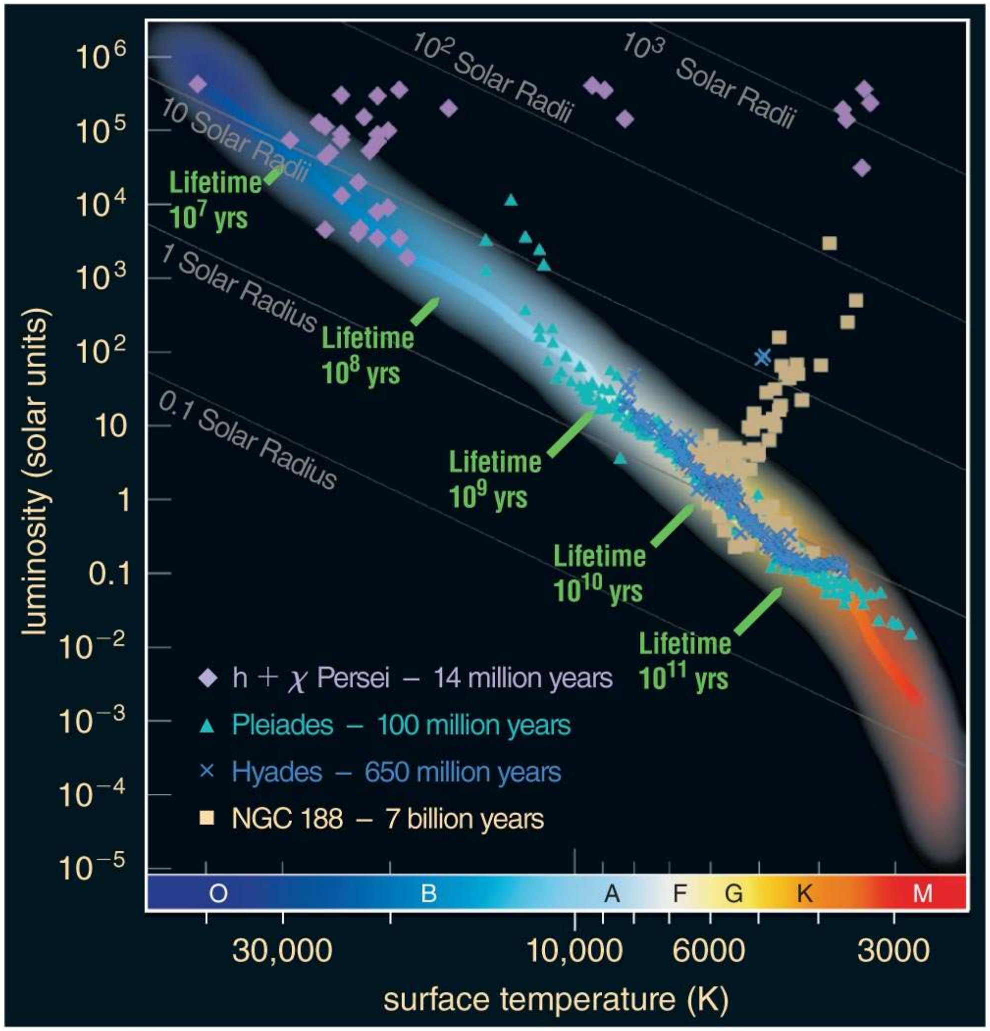


Clusters of stars are thought to have formed around the same time…

By cataloging the star-types in a cluster we find that the there a ‘turn-off’ point where the larger stars have begun leaving the main sequence…

Pleiades (shown in blue triangles) now has no stars with a life expectancy less than around 100 million years.

We can repeat this for multiple star clusters to determine their ages…



iClicker Question

Which type of star has the longest main-sequence lifetime?

A. A
B. B
C. G
D. O
E. M

iClicker Question

Which type of star has the longest main-sequence lifetime?

A. A
B. B
C. G
D. O
E. M

iClicker Question

Which of the following main-sequence turnoffs indicates the oldest globular cluster?

A. O5
B. O9
C. B7
D. B2
E. G2

iClicker Question

Which of the following main-sequence turnoffs indicates the oldest globular cluster?

A. O5
B. O9
C. B7
D. B2
E. G2

What’s Next?

Chapter 13: Star Stuff

13.1. Star Birth

- How do stars form?
- How massive are newborn Stars?

13.2. Life as a Low-Mass Star

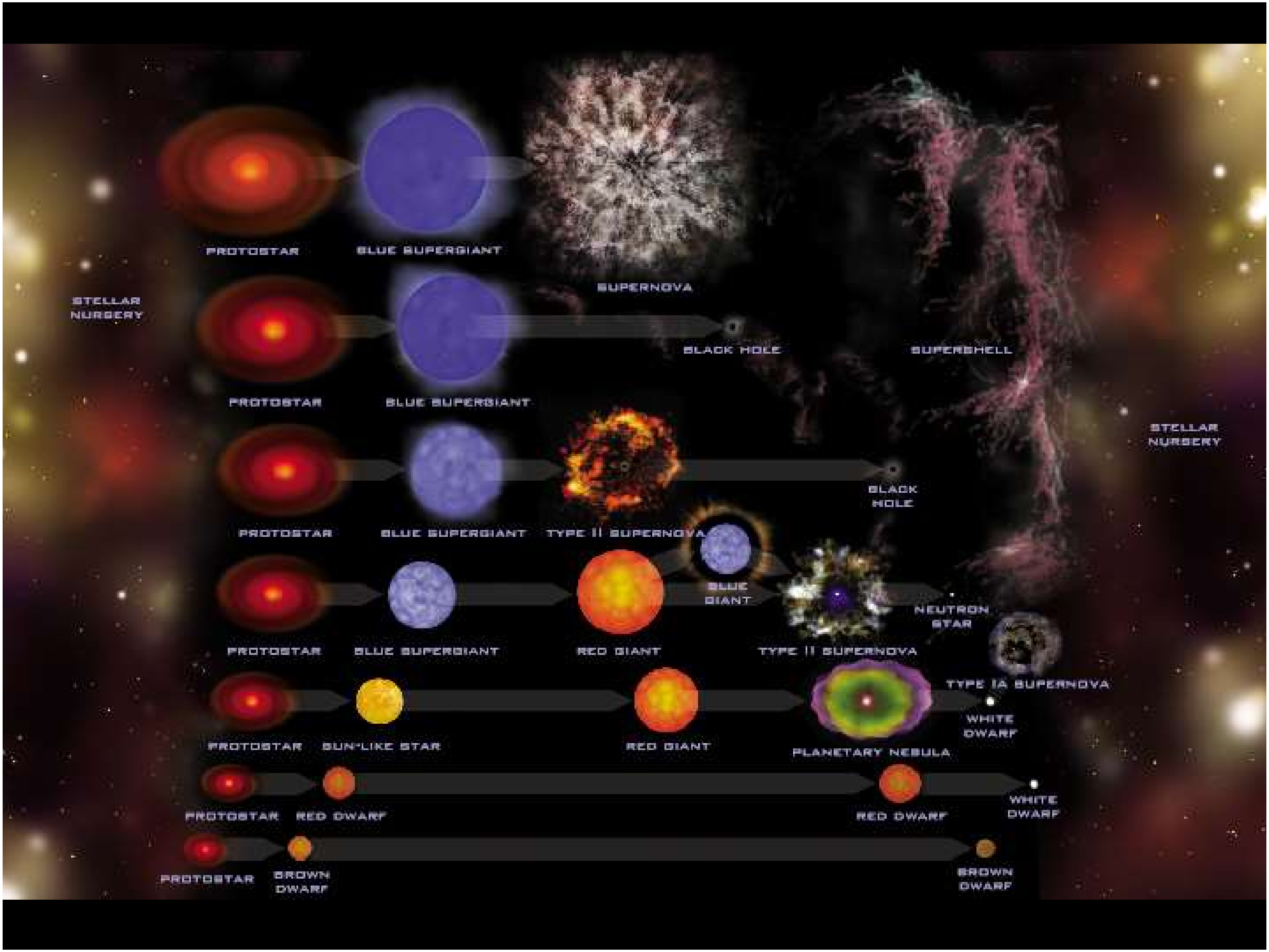
- What are the stages of a low-mass star?
- How does a low-mass star die?

13.3. Life as a High-Mass Star

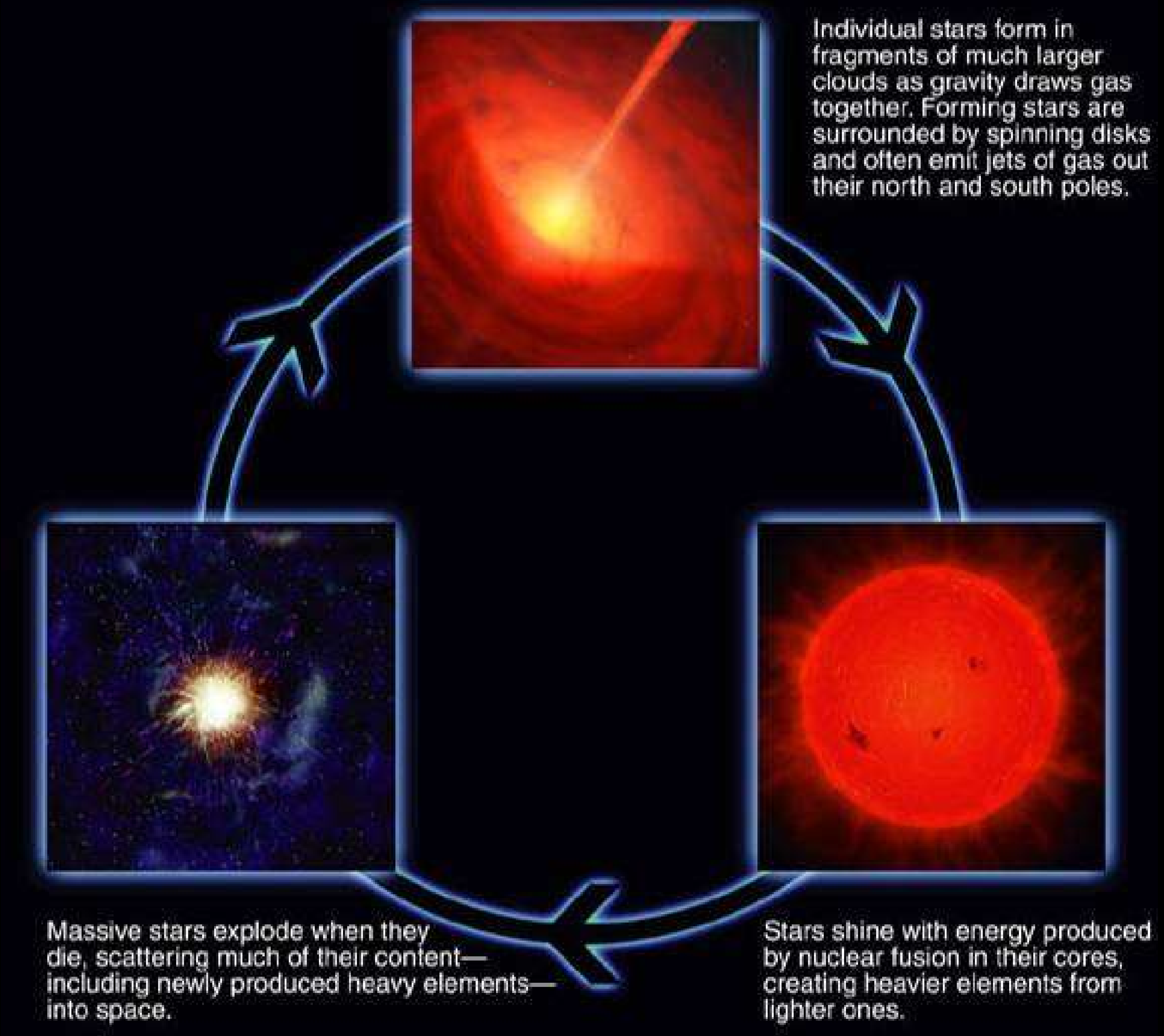
- What are the life stages of a high-mass star?
- How do high-mass stars make the elements necessary for life?
- How does a high-mass star die?

13.4. Stars in Close Binaries

- How are the lives of stars with close companions different?


STELLAR NURSERY
PROTOSTAR
BLUE SUPERGIANT
SUPERNOVA
SUPERSHELL
PROTOSTAR
BLUE SUPERGIANT
BLACK HOLE
STELLAR NURSERY
PROTOSTAR
BLUE SUPERGIANT
TYPE II SUPERNOVA
BLACK HOLE
PROTOSTAR
BLUE SUPERGIANT
RED GIANT
BLUE GIANT
TYPE II SUPERNOVA
NEUTRON STAR
TYPE IA SUPERNOVA
PROTOSTAR
SUN-LIKE STAR
RED GIANT
PLANETARY NEBULA
WHITE DWARF
PROTOSTAR
RED DWARF
RED DWARF
WHITE DWARF
PROTOSTAR
BROWN DWARF
BROWN DWARF

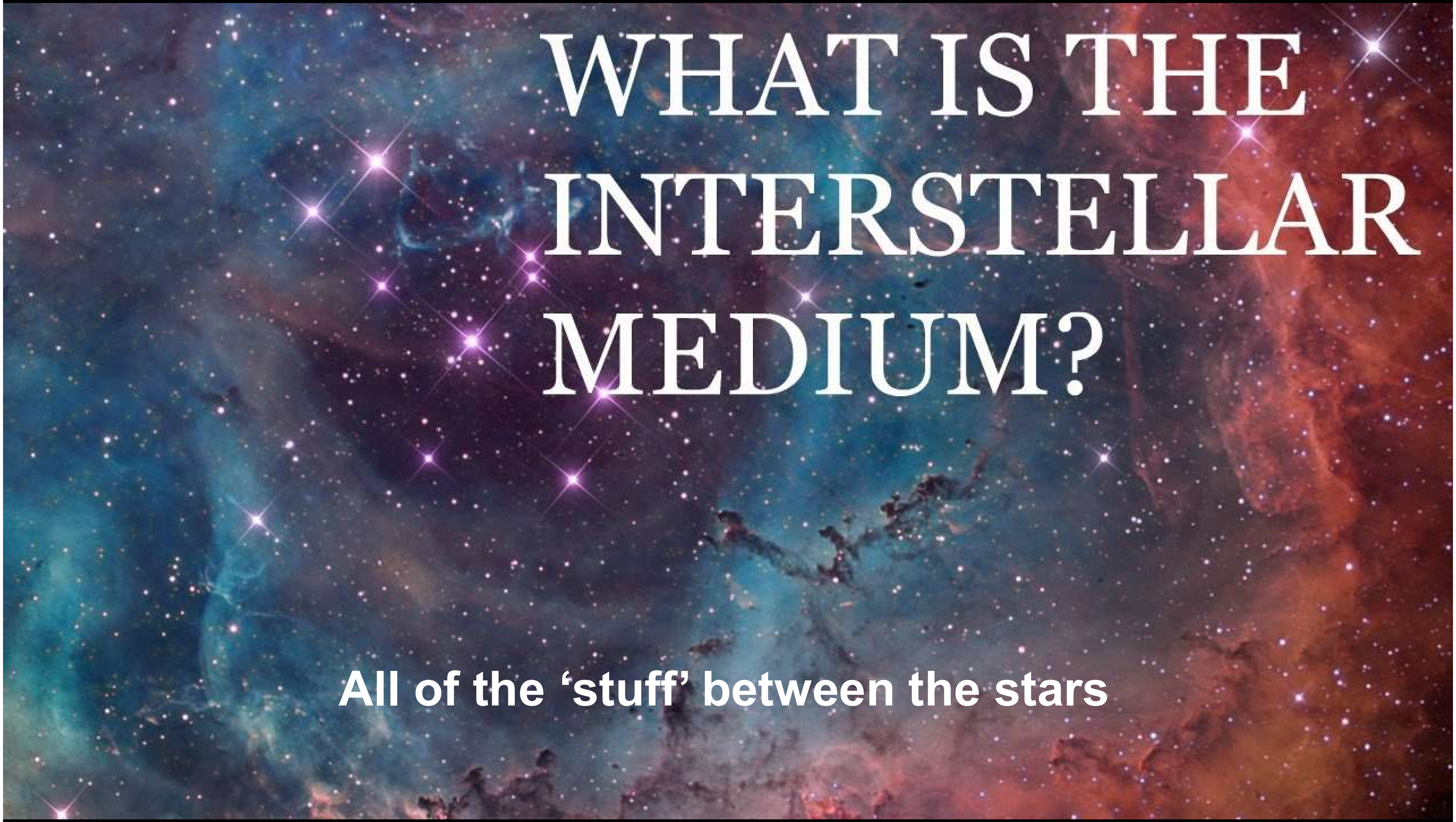
We are “star stuff” because the elements necessary for life were made in stars



Individual stars form in fragments of much larger clouds as gravity draws gas together. Forming stars are surrounded by spinning disks and often emit jets of gas out their north and south poles.

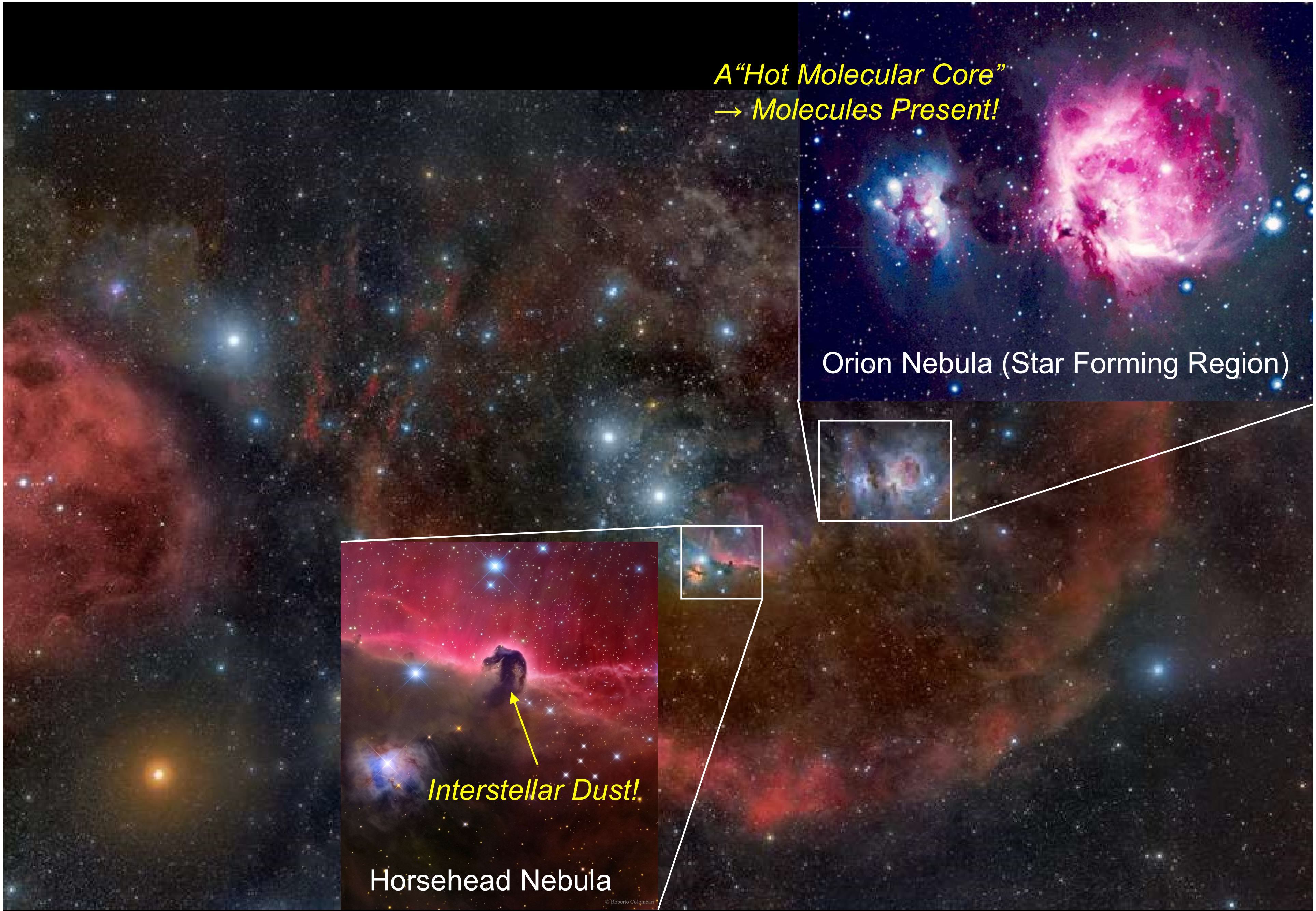
Stars shine with energy produced by nuclear fusion in their cores, creating heavier elements from lighter ones.

Massive stars explode when they die, scattering much of their content—including newly produced heavy elements—into space.



WHAT IS THE INTERSTELLAR MEDIUM?

All of the ‘stuff’ between the stars



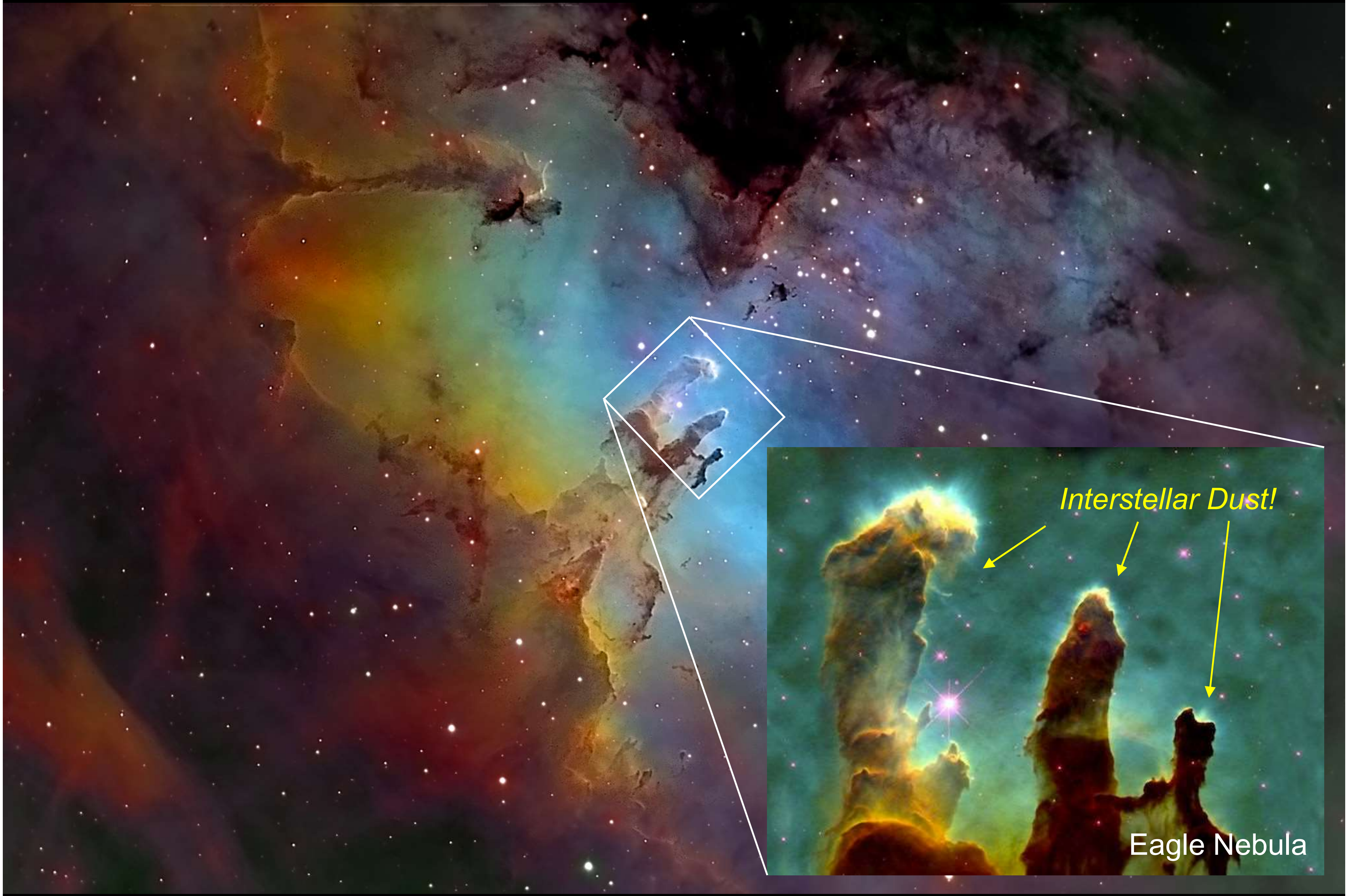
A"Hot Molecular Core"
→ Molecules Present!

Orion Nebula (Star Forming Region)

Interstellar Dust!

Horsehead Nebula

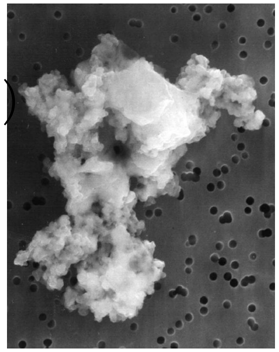
© Roberto Colombari

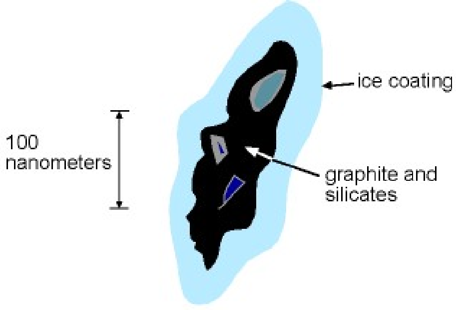

Interstellar Dust!
Eagle Nebula

Interstellar Dust Clouds

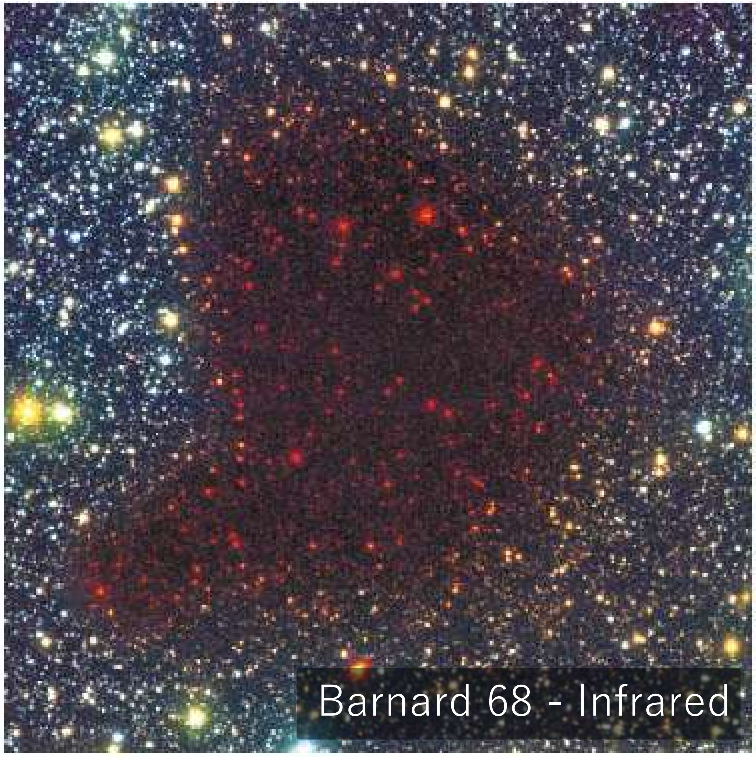
Physical Conditions:

- Dust is minor component ~ 1% (99% gas)
- VERY COLD, ~ 10 Kelvin inside clouds
- Pressure ~ 10^{-14} Torr…
- *Harsh Radiation Environment*





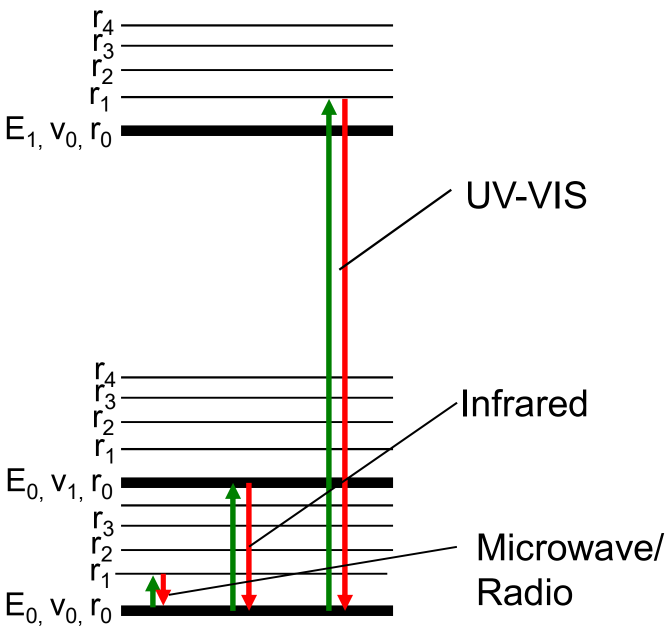
A typical dust grain (note the tiny scale!).



Interaction Between Electromagnetic Radiation & Matter

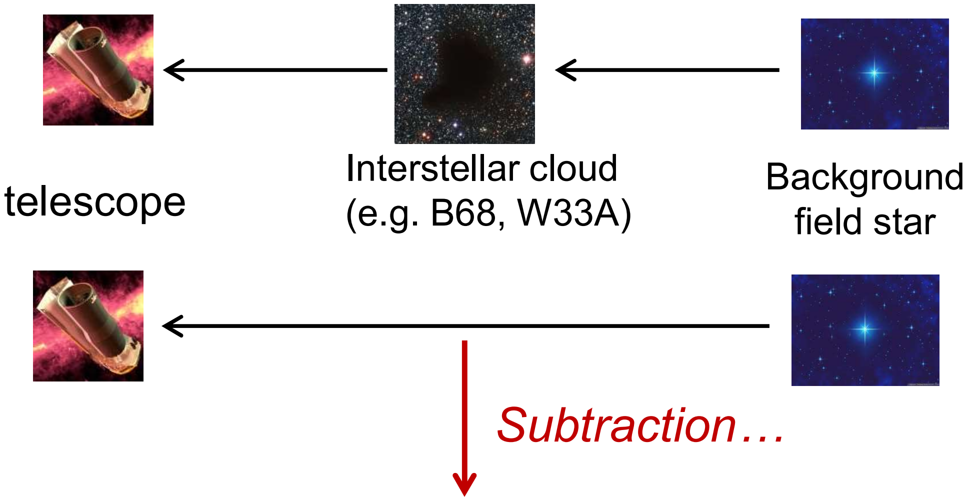
Absorption & Emission: tell us about specific *allowed* transitions within the molecules of interest

Electronic transitions = UV-VIS
Vibrational transitions = Infrared
Rotational transitions = Microwave



UV photons are energetic enough to cause bond-rupture processes

Inventory of Interstellar Ices

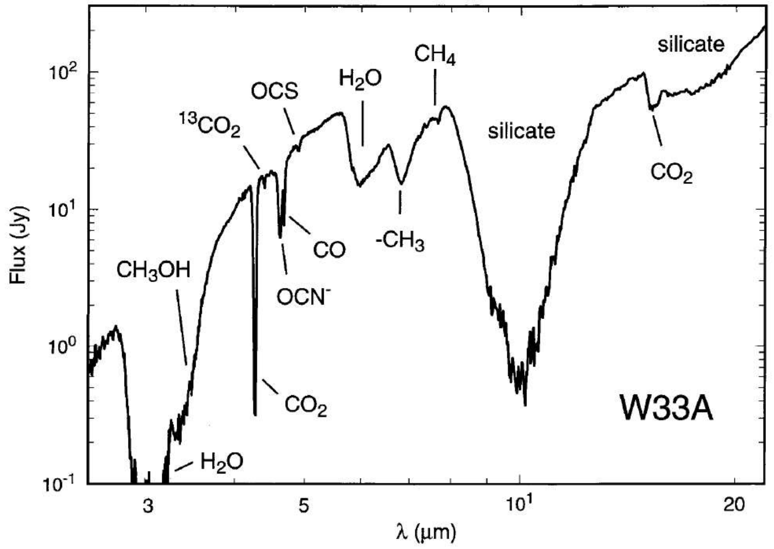


telescope

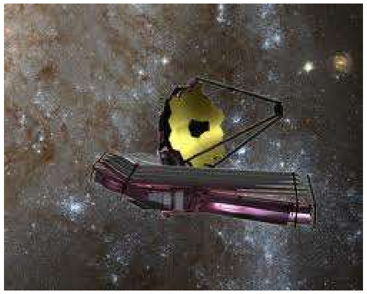
Interstellar cloud
(e.g. B68, W33A)

Background
field star

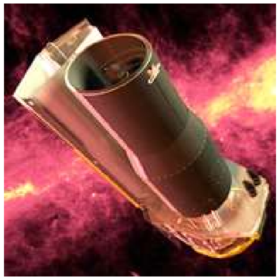
Subtraction…

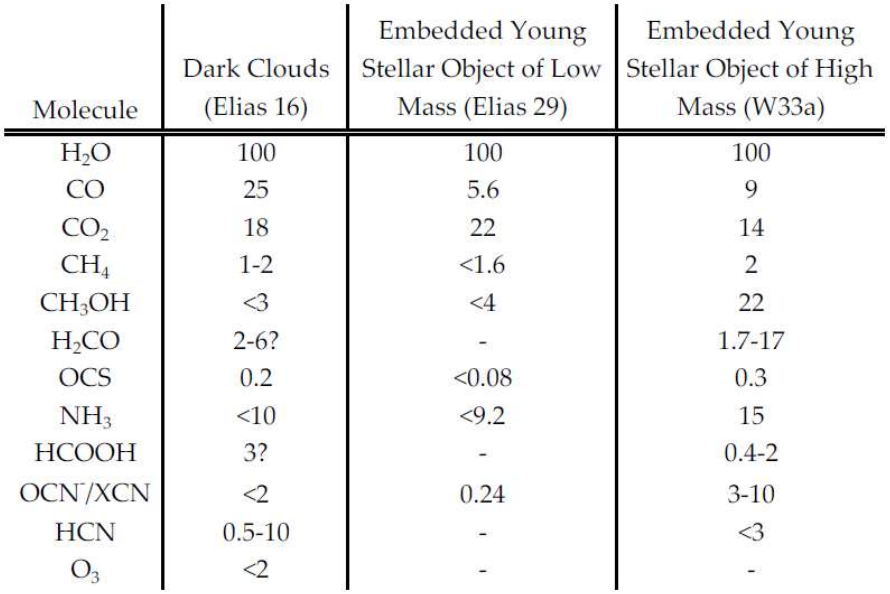


James-Webb



Spitzer





Molecule	Dark Clouds (Elias 16)	Embedded Young Stellar Object of Low Mass (Elias 29)	Embedded Young Stellar Object of High Mass (W33a)
H_2O	100	100	100
CO	25	5.6	9
CO_2	18	22	14
CH_4	1-2	<1.6	2
CH_3OH	<3	<4	22
H_2CO	2-6?	-	1.7-17
OCS	0.2	<0.08	0.3
NH_3	<10	<9.2	15
HCOOH	3?	-	0.4-2
OCN^-/XCN	<2	0.24	3-10
HCN	0.5-10	-	<3
O_3	<2	-	-

Characteristic Infrared Vibrations of Molecules

Classification of Interstellar Clouds

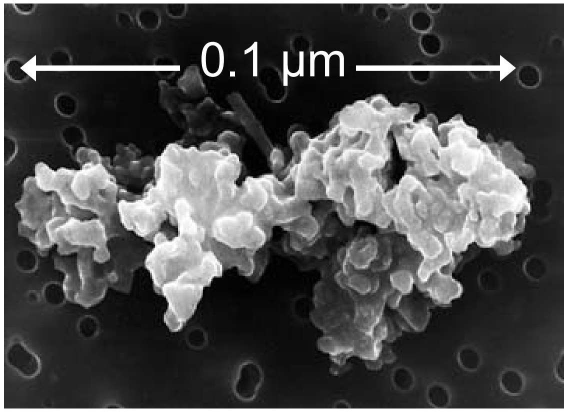
Averaged Composition

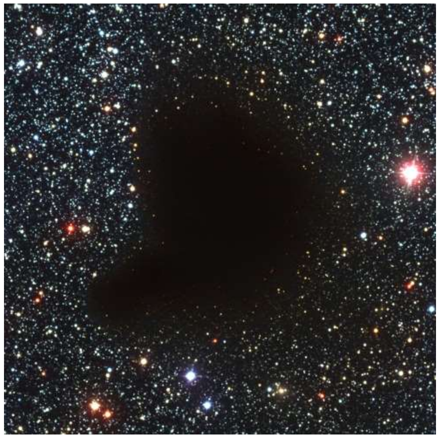
Gas phase (99%)

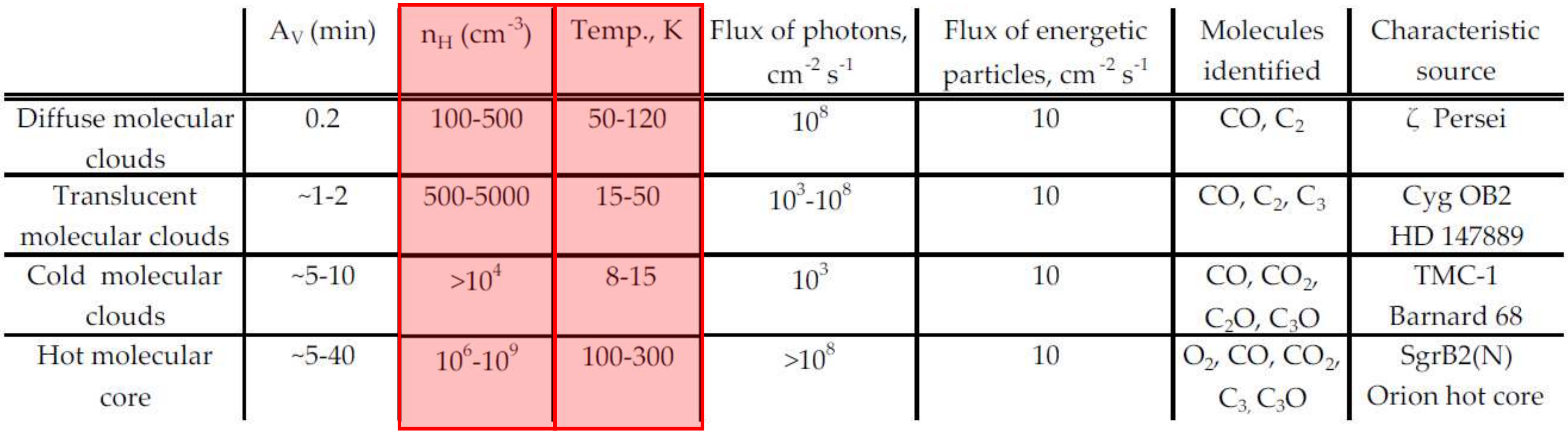
1 H atom cm^{-3}

Solid phase (1%)

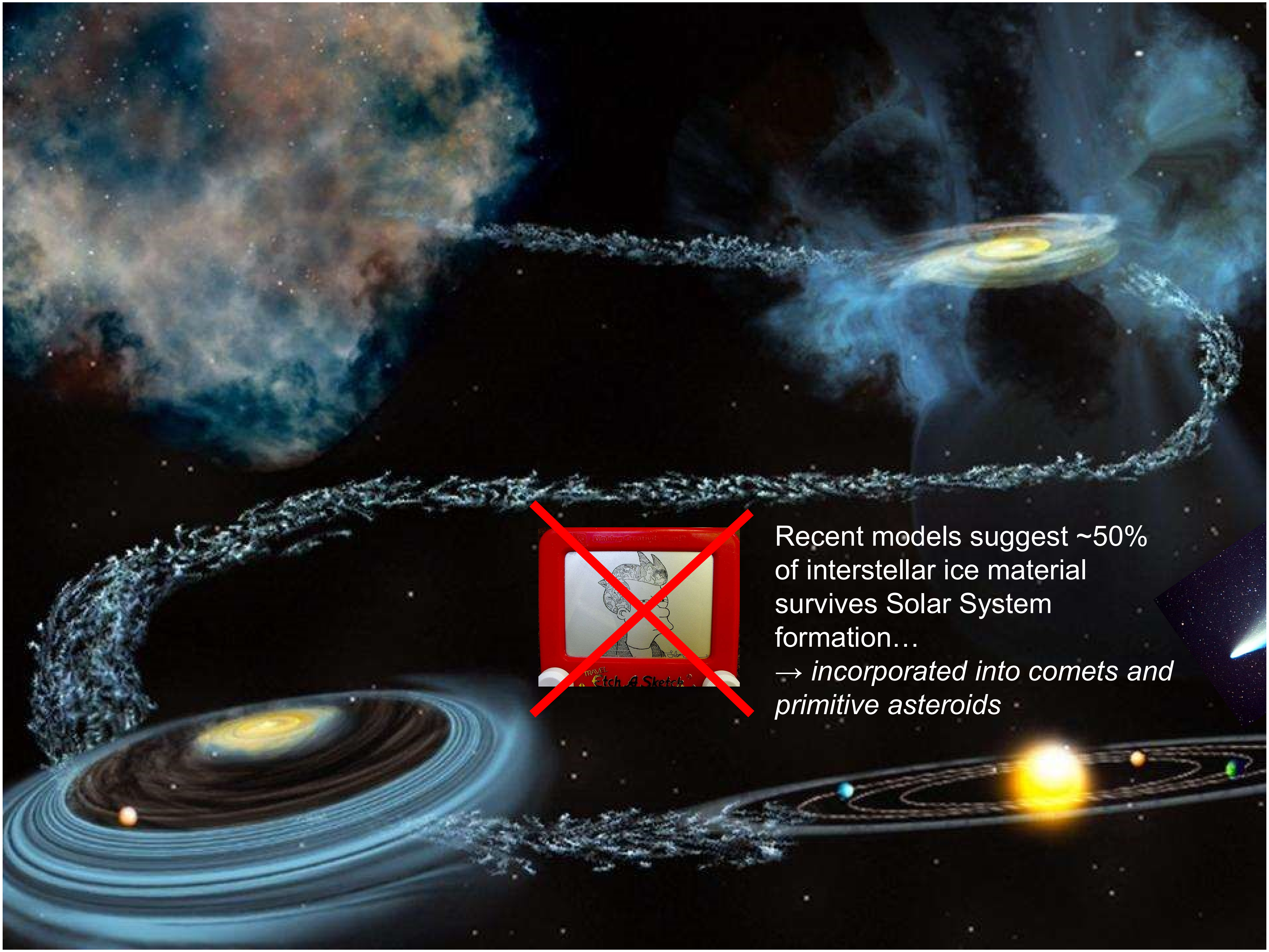
10^{-11} grains cm^{-3}







	A_V (min)	n_H (cm^{-3})	Temp., K	Flux of photons, cm^{-2} s^{-1}	Flux of energetic particles, cm^{-2} s^{-1}	Molecules identified	Characteristic source
Diffuse molecular clouds	0.2	100-500	50-120	10^8	10	CO, C_2	ζ Persei
Translucent molecular clouds	~1-2	500-5000	15-50	10^3-10^8	10	CO, C_2, C_3	Cyg OB2 HD 147889
Cold molecular clouds	~5-10	>10^4	8-15	10^3	10	CO, CO_2, C_2O, C_3O	TMC-1 Barnard 68
Hot molecular core	~5-40	10^6-10^9	100-300	>10^8	10	O_2, CO, CO_2, C_3, C_3O	SgrB2(N) Orion hot core

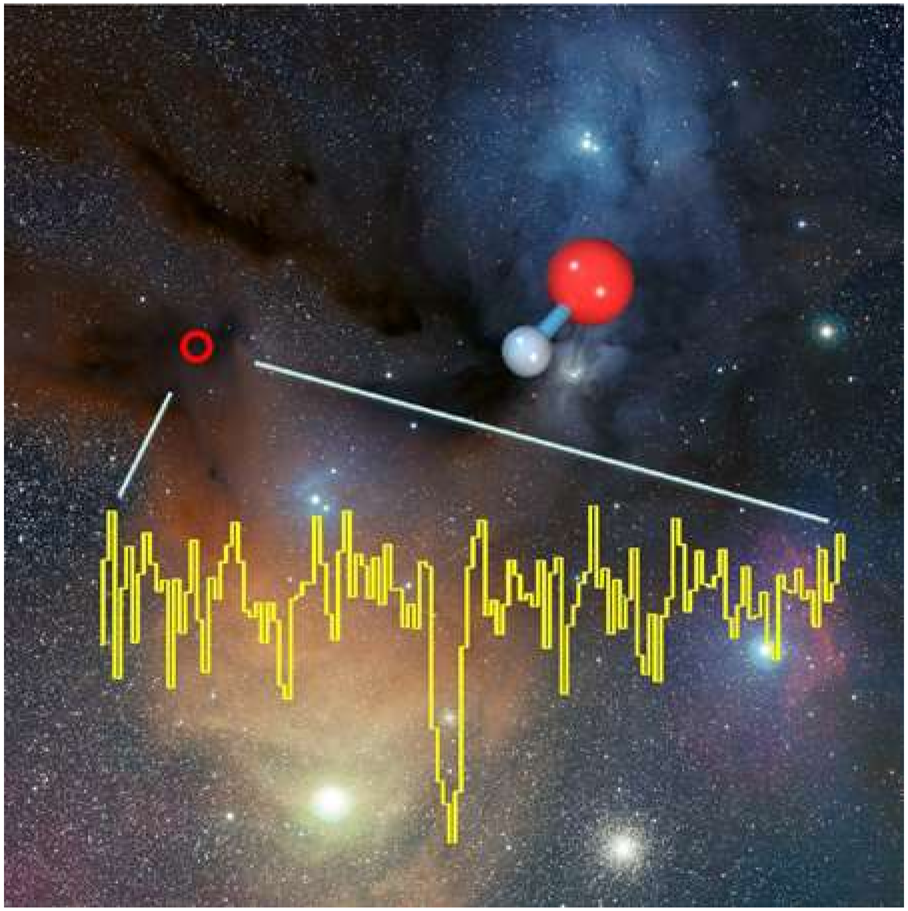


Recent models suggest ~50% of interstellar ice material survives Solar System formation…

→ *incorporated into comets and primitive asteroids*

Detection of Gas-phase Interstellar Species

Harsh irradiation environment → Surely nothing should be there?!? (think of all the UV radiation from O and B type stars!)



Many molecular species have been identified by their emission in the microwave region (low-lying rotational energy levels)

Inventory of Interstellar Molecules Detected to Date

# Atoms	Molecule	Designation	Mass	Ions
2	AlCl	Aluminium monochloride[8][9]	62.5	—
2	AlF	Aluminium monofluoride[8][10]	46	—
2	AlO	Aluminium monoxide[11]	43	—
2	C2	Diatomic carbon[12][13]	24	—
2	—	Fluoromethylidynium	31	CF+[14]
2	CH	Methylidyne radical[15]	13	CH+[16]
2	CN	Cyanogen radical[8][15][17][18]	26	CN+,[19] CN-[20]
2	CO	Carbon monoxide[8]	28	CO+[21]
2	CP	Carbon monophosphide[18]	43	—
2	CS	Carbon monosulfide[8]	44	—
2	FeO	Iron(II) oxide[22]	82	—
2	H2	Molecular hydrogen[23]	2	—
2	HCl	Hydrogen chloride[24]	36.5	—
2	HF	Hydrogen fluoride[25]	20	—
2	HO	Hydroxyl radical[8]	17	OH+[26]
2	KCl	Potassium chloride[8][9]	75.5	—
2	NH	Nitrogen monohydride[27][28]	15	—
2	N2	Molecular nitrogen[29][30]	28	—
2	NO	Nitric oxide[31]	30	NO+[19]
2	NS	Nitrogen sulfide[8]	46	—

Inventory of Interstellar Molecules Detected to Date

# Atoms	Molecule	Designation	Mass	Ions
2	NaCl	Sodium chloride[8][9]	58.5	—
2	—	Magnesium monohydride cation	25.3	MgH+[19]
2	NaI	Sodium iodide[32]	150	—
2	O2	Molecular oxygen[33]	32	—
2	PN	Phosphorus nitride[34]	45	—
2	PO	Phosphorus monoxide[35]	47	—
2	SH	Sulfur monohydride[36]	33	SH+[37]
2	SO	Sulfur monoxide[8]	48	SO+[16]
2	SiC	Carborundum[8][38]	40	—
2	SiN	Silicon mononitride[8]	42	—
2	SiO	Silicon monoxide[8]	44	—
2	SiS	Silicon monosulfide[8]	60	—
3	AlNC	Aluminium isocyanide[8]	53	—
3	AlOH	Aluminium hydroxide[40]	44	—
3	C3	Tricarbon[13]	36	—
3	C2H	Ethynyl radical[8][17]	25	—
3	C2O	Dicarbon monoxide[41]	40	—
3	C2S	Thioxoethenylidene[42]	56	—
3	C2P	—[43]	55	—

Inventory of Interstellar Molecules Detected to Date

# Atoms	Molecule	Designation	Mass	Ions
3	CO2	Carbon dioxide[44]	44	—
3	FeCN	Iron cyanide[45]	82	—
3	—	Protonated molecular hydrogen	3	H3+[3][39]
3	H2C	Methylene[12]	14	—
3	—	Chloronium	37.5	H2Cl+[46]
3	H2O	Water[47]	18	H2O+[48]
3	H2S	Hydrogen sulfide[8]	34	—
3	HCN	Hydrogen cyanide[8][17][49]	27	—
3	HNC	Hydrogen isocyanide[50]	27	—
3	HCO	Formyl radical[51]	29	HCO+[16][51][52]
3	HCP	Phosphaethyne[53]	44	—
3	—	Thioformyl	45	HCS+[16][52]
3	HNC	Hydrogen isocyanide[54]	27	—
3	—	Diazenylium	29	HN2+[52]
3	HNO	Nitroxyl[55]	31	—
3	—	Isoformyl	29	HOC+[17]
3	KCN	Potassium cyanide[8]	65	—
3	MgCN	Magnesium cyanide[8]	50	—
3	MgNC	Magnesium isocyanide[8]	50	—
3	NH2	Amino radical[56]	16	—

Inventory of Interstellar Molecules Detected to Date

# Atoms	Molecule	Designation	Mass	Ions
3	—	—	29	N2H+[16][57]
3	N2O	Nitrous oxide[58]	44	—
3	NaCN	Sodium cyanide[8]	49	—
3	NaOH	Sodium hydroxide[59]	40	—
3	OCS	Carbonyl sulfide[60]	60	—
3	O3	Ozone[61]	48	—
3	SO2	Sulfur dioxide[8][62]	64	—
3	c-SiC2	c-Silicon dicarbide[8][38]	52	—
3	SiCN	Silicon carbonitride[63]	54	—
3	SiNC	Silicon naphthalocyanine[64]	54	—
4	CH3	Methyl[66]	15	—
4	l-C3H	Propynylidyne[8][67]	37	—
4	c-C3H	Cyclopropynylidyne[68]	37	—
4	C3N	Cyanoethynyl[12]	50	C3N-[43]
4	C3O	Tricarbon monoxide[67]	52	—
4	C3S	Tricarbonsulfide[8][42]	68	—
4	—	Hydronium	19	H3O+[69]
4	C2H2	Acetylene[70]	26	—
4	H2CN	Methylene amidogen[71]	28	H2CN+[16]

Inventory of Interstellar Molecules Detected to Date

# Atoms	Molecule	Designation	Mass	Ions
4	H2CO	Formaldehyde[72]	30	—
4	H2CS	Thioformaldehyde[73]	46	—
4	HCCN	—[74]	39	—
4	—	Protonated hydrogen cyanide	28	HCNH+[52]
4	—	Protonated carbon dioxide	45	HOCO+[75]
4	HCNO	Fulminic acid[76]	43	—
4	HOCN	Cyanic acid[77]	43	—
4	HOOH	Hydrogen peroxide[78]	34	—
4	HNCO	Isocyanic acid[62]	43	—
4	HNCS	Isothiocyanic acid[79]	59	—
4	NH3	Ammonia[8][80]	17	—
4	HSCN	Thiocyanic acid[81]	59	—
4	SiC3	Silicon tricarbide[8]	64	—
5	C5	—[13]	60	—
5	CH4	Methane[27][70]	16	—
5	c-C3H2	Cyclopropenylidene[17][83][84]	38	—
5	l-H2C3	Propadienylidene[84]	38	—
5	H2CCN	Cyanomethyl[75]	40	—
5	H2C2O	Ketene[62]	42	—

Inventory of Interstellar Molecules Detected to Date

# Atoms	Molecule	Designation	Mass	Ions
5	H_2CNH	Methylenimine[85]	29	—
5	—	Protonated formaldehyde	31	H_2COH^+[86]
5	C_4H	Butadiynyl[8]	49	$C_4H^–$[87]
5	HC_3N	Cyanoacetylene[8][17][52][84][88]	51	—
5	HCC-NC	Isocyanoacetylene[89]	51	—
5	HCOOH	Formic acid[84]	46	—
5	NH_2CN	Cyanamide[90]	42	—
5	HC(O)CN	Cyanoformaldehyde[91]	55	—
5	SiC_4	Silicon-carbide cluster[38]	92	—
5	SiH_4	Silane[92]	32	—
6	c-H_2C_3O	Cyclopropenone[93]	54	—
6	C_2H_4	Ethylene[70]	28	—
6	C_5H	Pentynylidyne[8][42]	61	—
6	C_5N	Cyanobutadiynyl[96]	74	—
6	CH_2CNH	Ketenimine[83]	40	—
6	CH_3CN	Acetonitrile[62][94]	40	—
6	CH_3NC	Methyl isocyanide[94]	40	—
6	CH_3OH	Methanol[62]	32	—
6	CH_3SH	Methanethiol[79]	48	—

Inventory of Interstellar Molecules Detected to Date

# Atoms	Molecule	Designation	Mass	Ions
6	HC2CHO	Propynal[97]	54	—
6	HC4N	—[8]	63	—
6	HCONH2	Formamide[93]	44	—
6	l-H2C4	Diacetylene[8][95]	50	—
6	—	Protonated cyanoacetylene	52	HC3NH+[52]
7	c-C2H4O	Ethylene oxide[99]	44	—
7	CH3C2H	Methylacetylene[17]	40	—
7	H3CNH2	Methylamine[100]	31	—
7	CH2CHCN	Acrylonitrile[62][94]	53	—
7	H2CHCOH	Vinyl alcohol[98]	44	—
7	C6H	Hexatriynyl[8][42]	73	C6H–[84][101]
7	HC4CN	Cyanodiacetylene[62][88][94]	75	—
7	CH3CHO	Acetaldehyde[8][99]	44	—
8	H3CC2CN	Methylcyanoacetylene[103]	65	
8	H2COHCHO	Glycolaldehyde[104]	60	
8	HCOOCH3	Methyl formate[62][84][104]	60	
8	CH3COOH	Acetic acid[102]	60	
8	H2C6	Hexapentaenylidene[8][95]	74	

Inventory of Interstellar Molecules Detected to Date

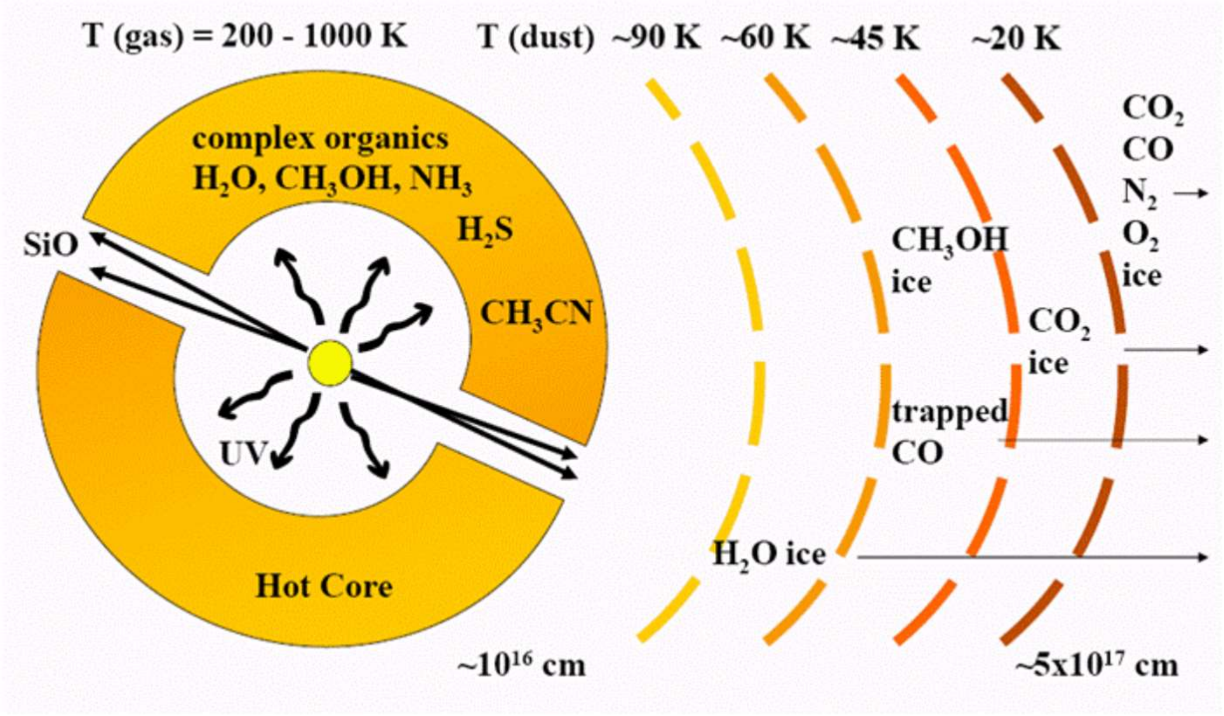
# Atoms	Molecule	Designation	Mass	Ions
8	CH2CHCHO	Propenal[83]	56	
8	CH2CCHCN	Cyanoallene[83][103]	65	
8	C7H	Heptatrienyl radical[105]	85	
8	NH2CH2CN	Aminoacetonitrile[106]	56	
9	CH3C4H	Methyldiacetylene[107]	64	—
9	CH3OCH3	Dimethyl Ether[108]	46	—
9	CH3CH2CN	Propionitrile[8][62][84][94]	55	—
9	CH3CONH2	Acetamide[83][93]	59	—
9	CH3CH2OH	Ethyl Alcohol[109]	46	—
9	C8H	Octatetraynyl[110]	97	C8H–[111]
9	HC7N	Cyanohexatriyne or Cyanotriacetylene[8][80][112][113]	99	—
9	CH3CHCH2	Propylene (propene)[114]	42	—
10	(CH3)2CO	Acetone[62][115]	58	—
10	(CH2OH)2	Ethylene glycol[116][117]	62	—
10	CH3CH2CHO	Propanal[83]	58	—
10	CH3C5N	Methyl-cyano-diacetylene[83]	89	—
11	HC8CN	Cyanotetra-acetylene[8][112]	123	—
11	C2H5OCHO	Ethyl formate[118]	74	—

What is a Hot Molecular Core?

A region surrounding a young stellar object (a star) which starts to warm and sublimate the surrounding ices…

- Injects molecules into the gas phase (e.g., CH_3OH)

→ **Question:** Are molecules detected being released from the ices, or are they being formed in subsequent gas-phase processes?



Star-forming clouds

Newborn stars produce white patches in the cloud where starlight illuminates surrounding gas.

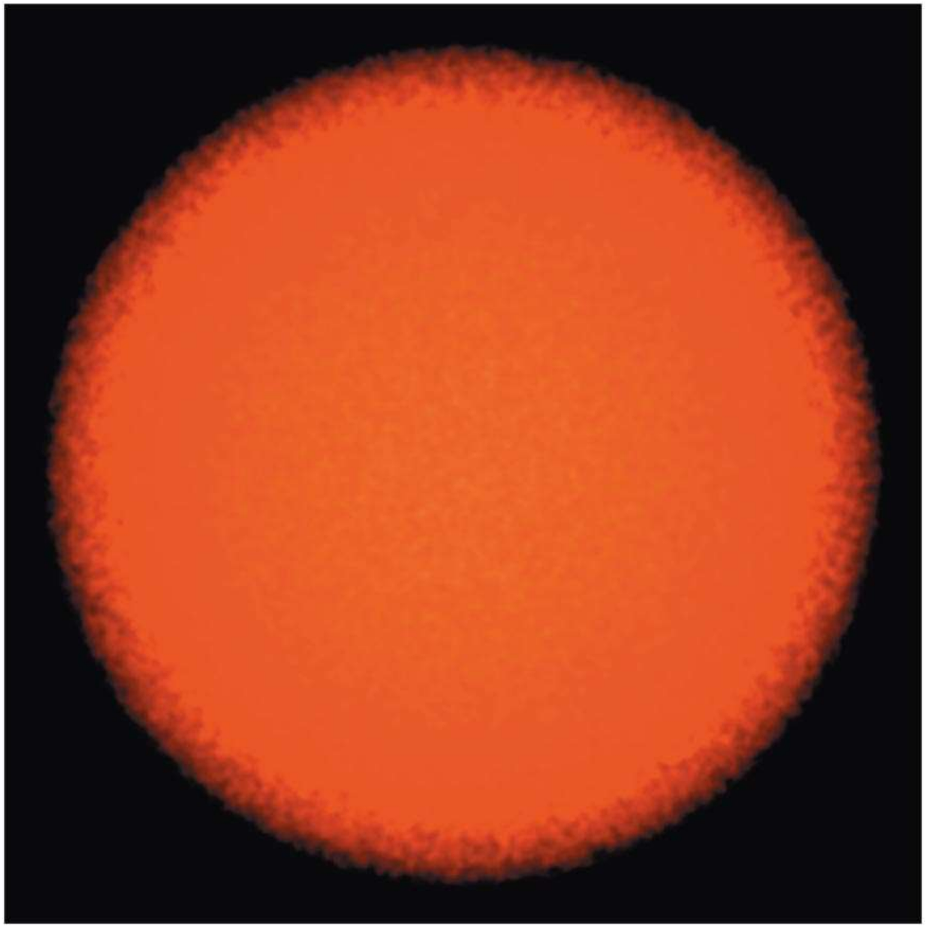
The cloud looks dark where dust particles block the light from more distant stars.

Only the coldest and densest clouds will lead to star formation

Conditions for Star Birth

- Star formation is actually a difficult process that does not *typically* happen spontaneously… why?
- Temperature acts as a pressure, even at the low temperatures of a cloud (say 30 K) this can be enough to resist gravity – up to a point…
- As a cloud becomes denser it can help overcome the outward pressure of temperature more effectively
- The relationship between pressure, density and gravity is described by the Jean’s instability relationship

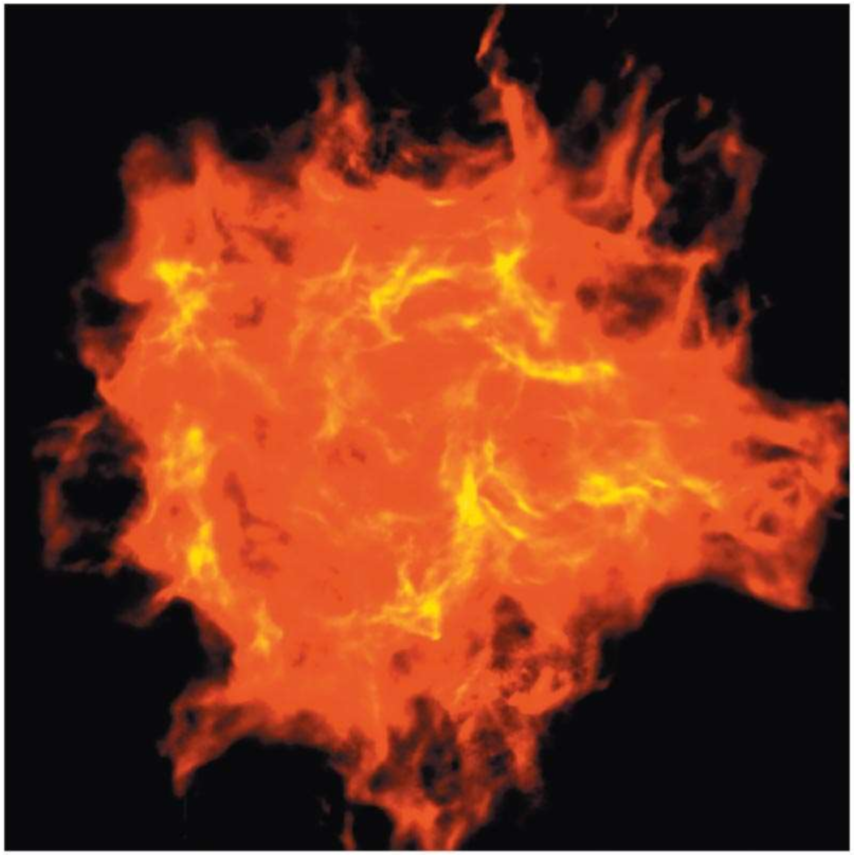
Simulation: Fragmentation of a Cloud



a The simulation begins with a turbulent gas cloud 1.2 light-years across, containing $50M_{\text{Sun}}$ of gas.

- This simulation begins with a turbulent cloud containing 50 solar masses of gas.

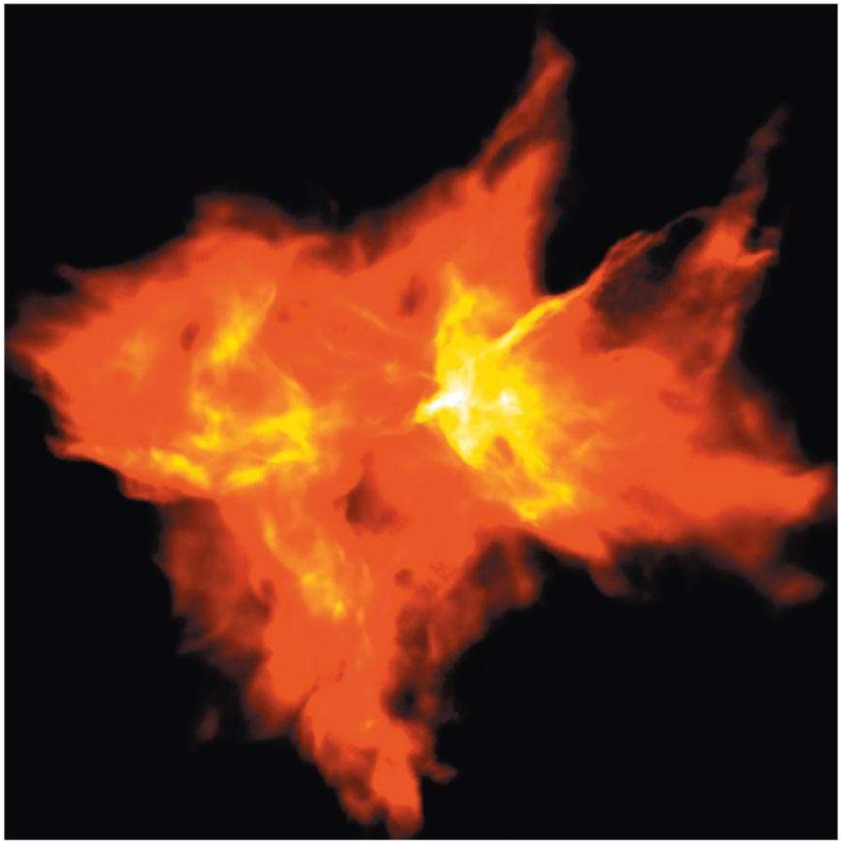
Simulation: Fragmentation of a Cloud



b Random motions in the cloud cause it to become lumpy, with some regions denser than others. If gravity can overcome pressure in these dense regions, they can collapse to form even denser lumps of matter.

- The random motions of different sections of the cloud cause it to become lumpy.

Simulation: Fragmentation of a Cloud



c The large cloud therefore fragments into many smaller lumps of matter, and each lump can go on to form one or more new stars.

- Each lump of the cloud in which gravity can overcome pressure can go on to become a star.
- A large cloud can make a whole cluster of stars.

Approximation to Jean’s Instability Criteria – Minimum Mass

Here is a simplified formula that gives an indication to the minimum mass required as a function of temperature and density:

$$M_{minimum} = 18M_{Sun}\sqrt{\frac{T^3}{n}}$$

Where *T* is temperature, in Kelvin, *n* is the gas density (in particles per cm^{-3})

Question: If a cloud has a temperature of 30 K, and an average temperature of 300 particles per cubic centimeter, what is the minimum mass needed for star formation to occur spontaneously?

Solution: Insert *T*=300 K and *n*=300 cm^{-3} into the equation.

$$M_{minimum} = 18M_{Sun}\sqrt{\frac{300^3}{300}} = 171M_{Sun}$$

Approximation to Jean's Instability Criteria – Minimum Mass

$$M_{minimum} = 18M_{Sun}\sqrt{\frac{T^3}{n}}$$

Incredibly sensitive to the temperature and quite sensitive to the number density…

- If T = 30 K, n = 300 cm^{-3}, $M_{minimum}$ = 171 M_{Sun}

Effect of temperature (typical for dense clouds):

- If T = 10 K, n = 300 cm^{-3}, $M_{minimum}$ = 33 M_{sun}

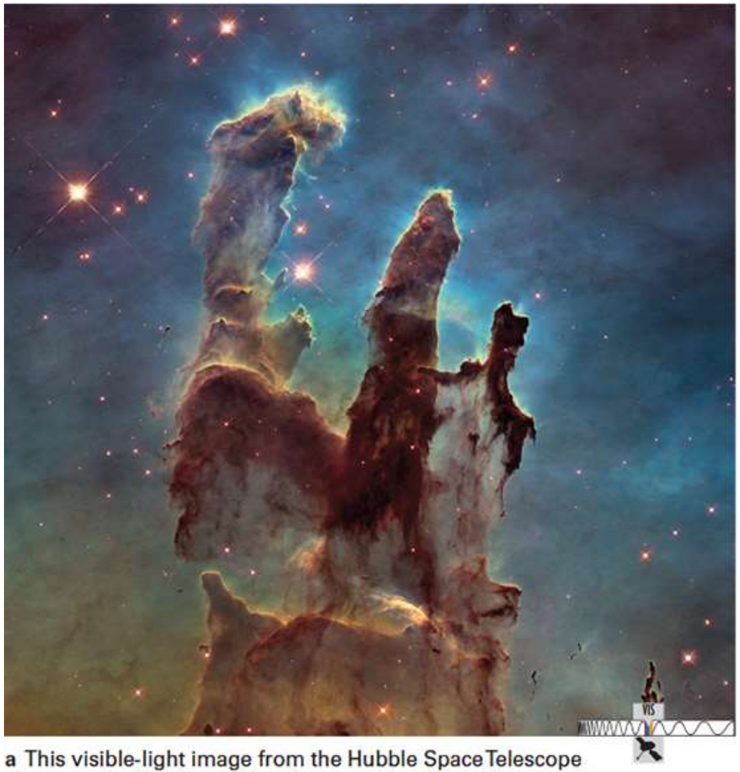
Effect of number density (typical for dense clouds):

- If T = 10 K, n = 104 cm^{-3}, $M_{minimum}$ = 6 M_{sun}

Not the full story: Cloud collapse may be triggered by an initial instability (e.g., a shock from a nearby supernova)

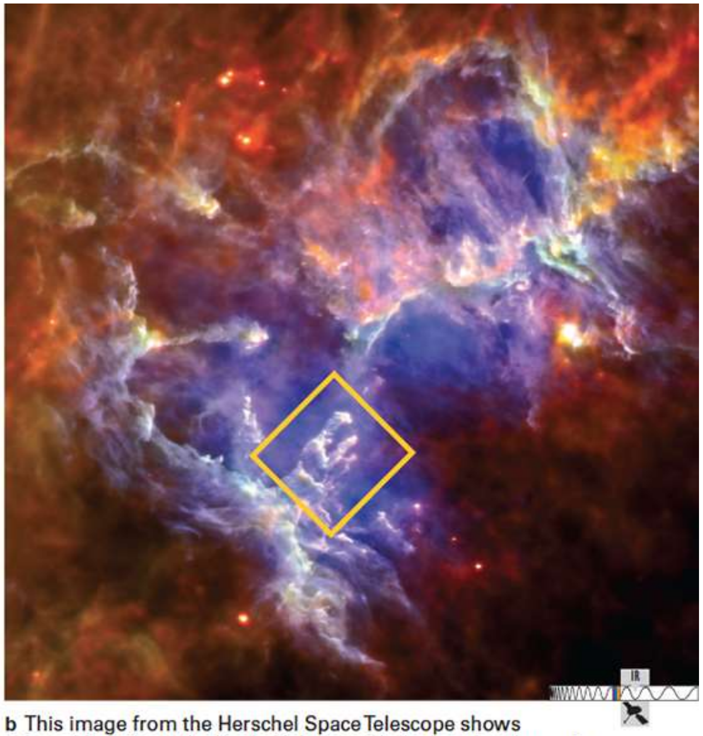
Hidden Star Formation: Glowing Dust Grains

- As stars begin to form, dust grains that absorb visible light heat up and emit infrared light.



a This visible-light image from the Hubble Space Telescope shows part of the Eagle Nebula, a gas cloud in which stars are currently forming.

In visible light, as in this image, the star forming regions still appear dark.



b This image from the Herschel Space Telescope shows infrared light from the Eagle Nebula, with the portion shown in part a outlined by the yellow square. Notice that the dark clouds in the visible-light image are glowing in the infrared image.

Long-wavelength infrared light is brightest from regions where many stars are currently forming.

Thought Question

What would happen to a contracting cloud fragment if it were not able to radiate away its thermal energy?

A. It would continue contracting, but its temperature would not change.
B. Its mass would increase.
C. Its internal pressure would increase.

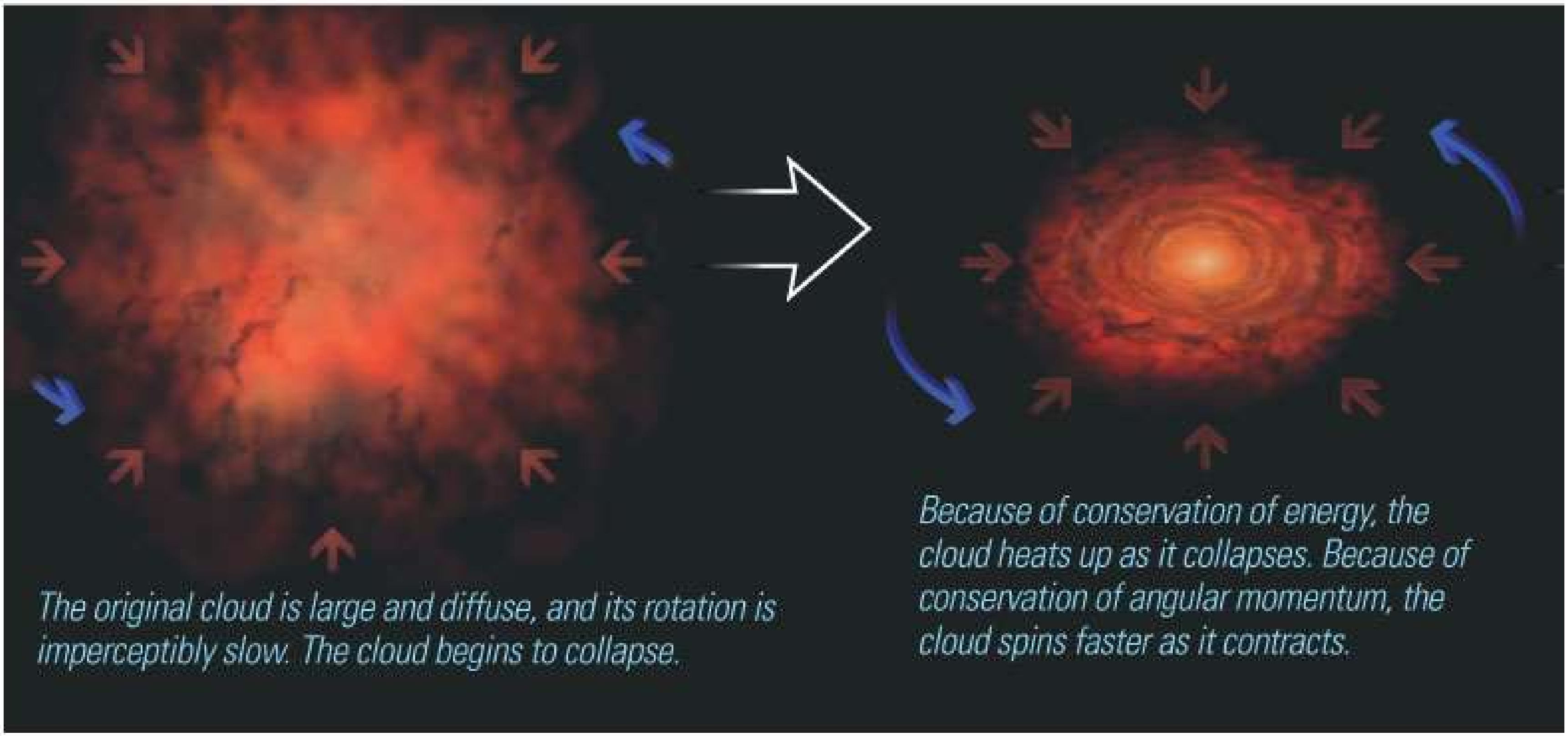
Thought Question

What would happen to a contracting cloud fragment if it were not able to radiate away its thermal energy?

A. It would continue contracting, but its temperature would not change.
B. Its mass would increase.
C. Its internal pressure would increase.

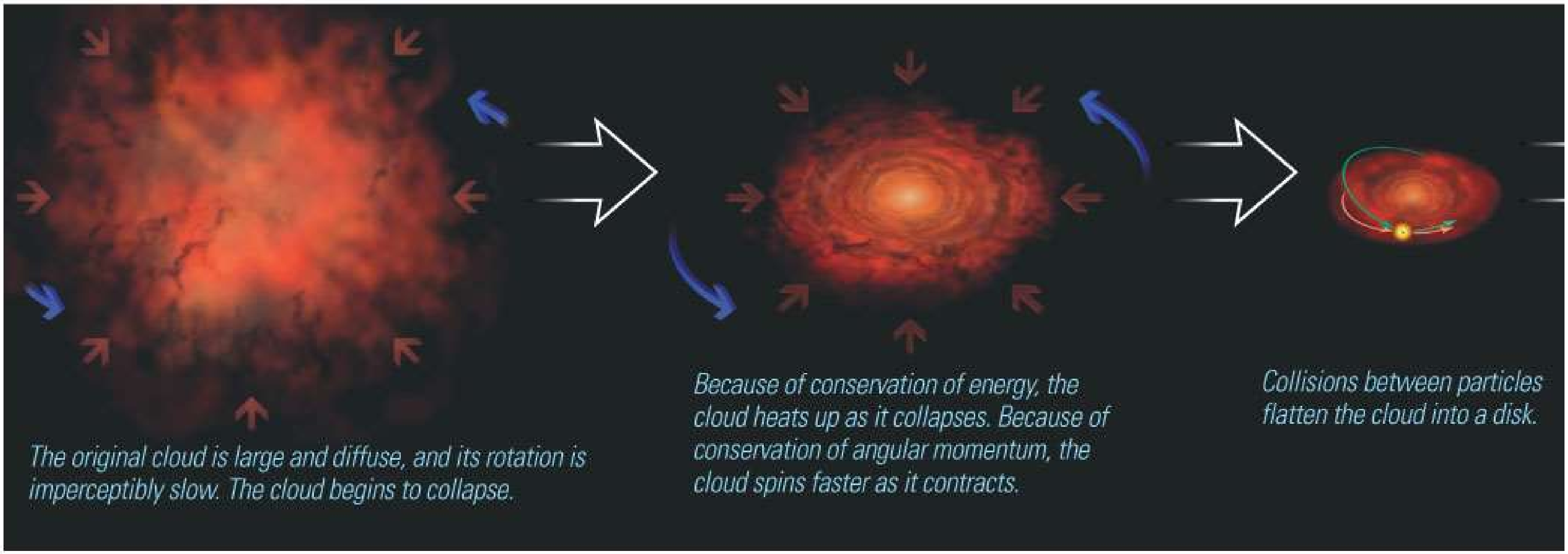
An Example of the Star Birth Process: Solar system formation

Cloud heats up as gravity causes it to contract due to *conservation of energy*. Contraction can continue if thermal energy is radiated away.



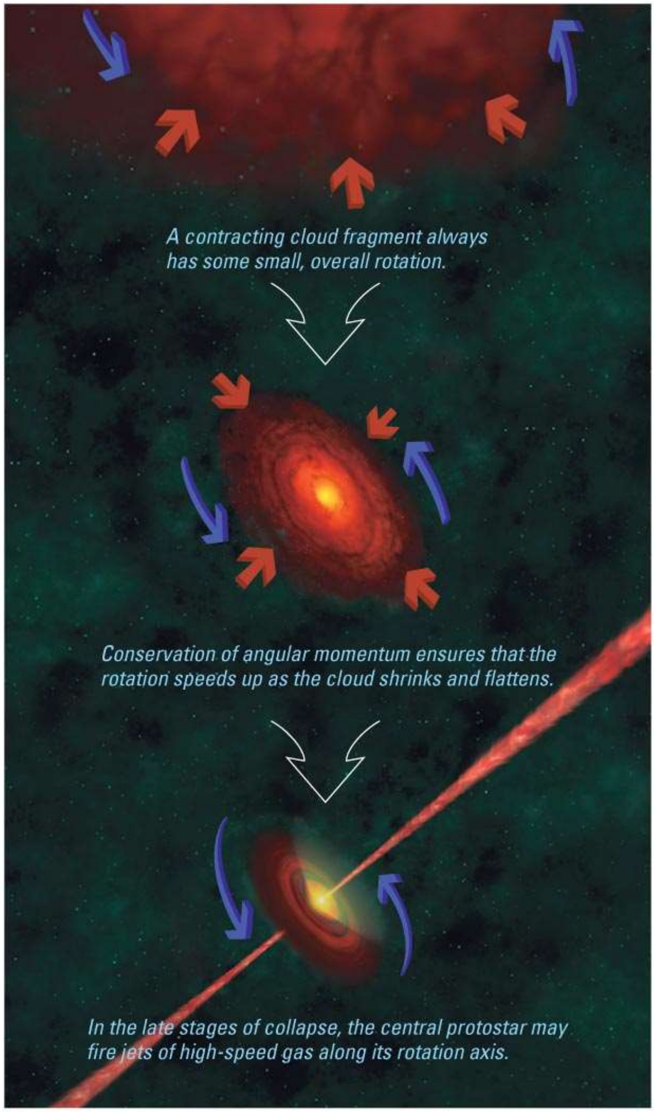
An Example of the Star Birth Process: Solar system formation

As gravity forces a cloud to become smaller, it begins to spin faster and faster, due to *conservation of angular momentum*.

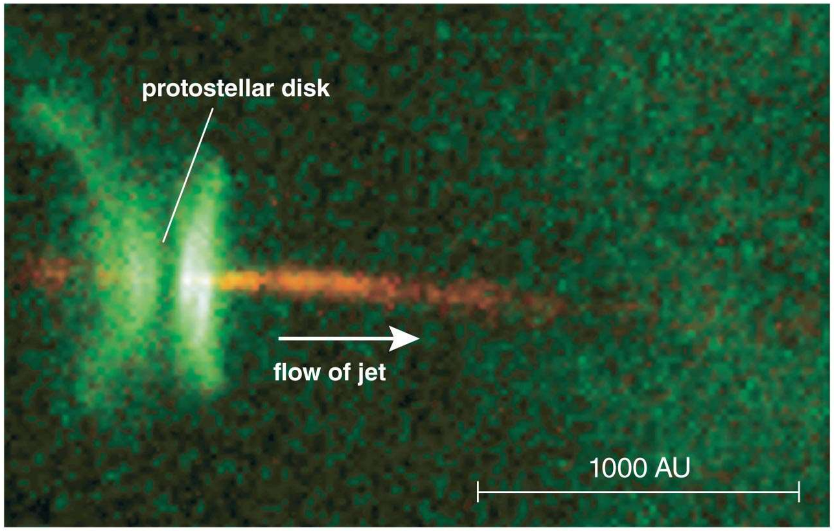


Collisions between particles in the cloud cause it to flatten into a disk with a highly circular orbit (low eccentricity).

Formation of Jets

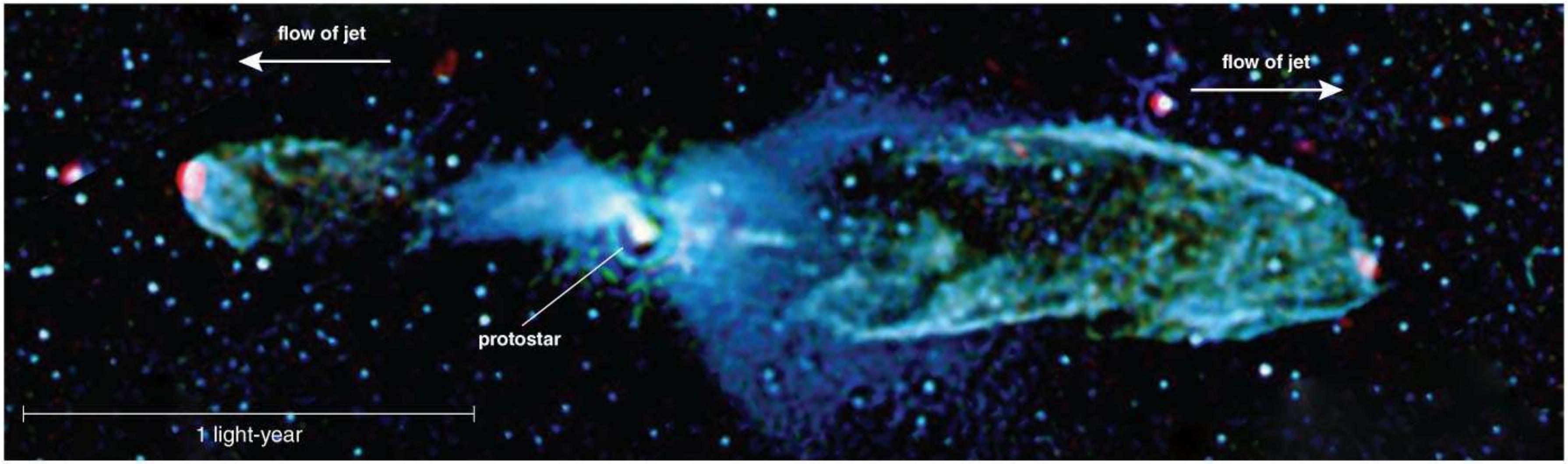


- Rotation also causes jets of matter to shoot out along the rotation axis.
- Jets are observed coming from the centers of disks around protostars.



b This photograph shows a close-up view of a jet (red) and a disk of gas (green) around a protostar. We are seeing the disk nearly edge-on. The top and bottom surfaces of the disk are glowing, but we cannot see the darker middle layers of the disk.

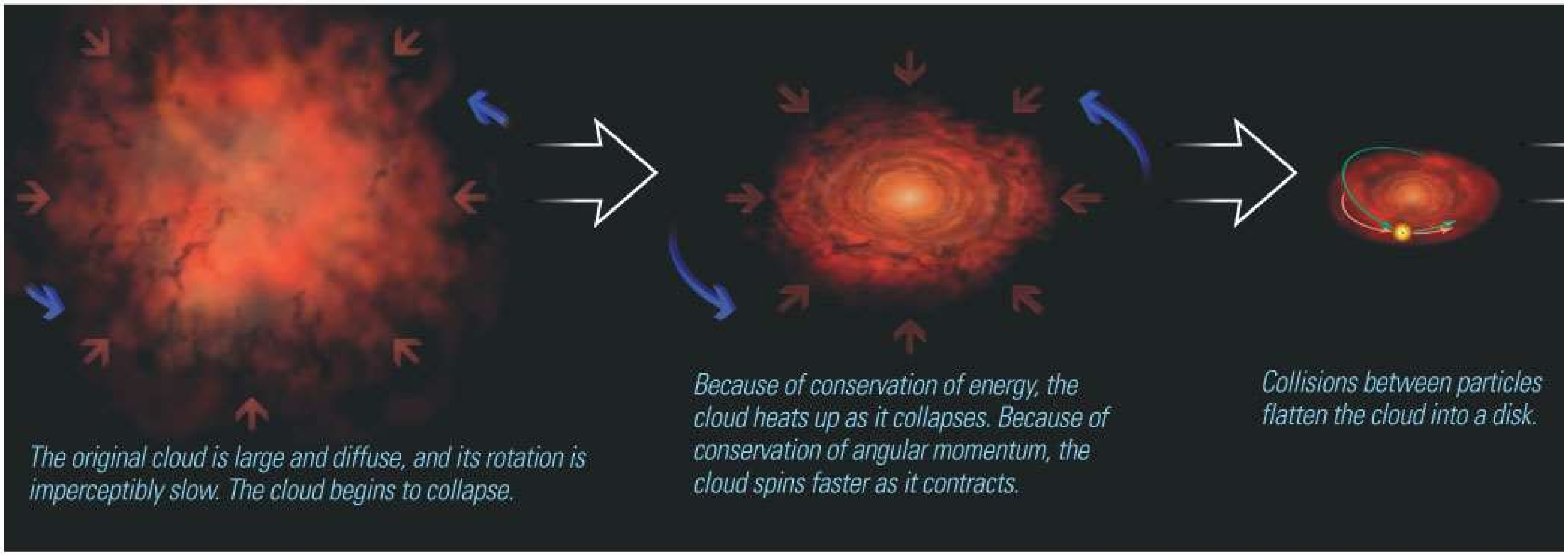
Formation of Jets



a This photograph shows two jets of material being shot in opposite directions by a protostar. The structures to the left and right of the protostar are formed as the jet material rams into surrounding interstellar gas.

Summary of Star Birth

1. Gravity causes gas cloud to shrink and fragment.
2. Core of shrinking cloud heats up.
3. When core gets hot enough, fusion begins and stops the shrinking.
4. New star achieves long-lasting state of balance

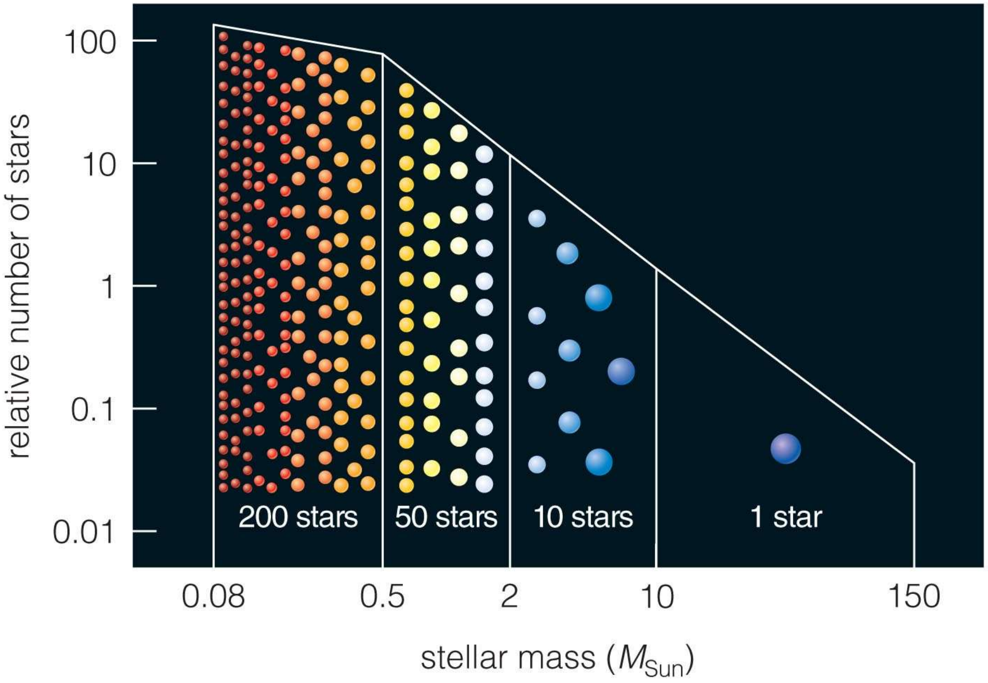


The original cloud is large and diffuse, and its rotation is imperceptibly slow. The cloud begins to collapse.

Because of conservation of energy, the cloud heats up as it collapses. Because of conservation of angular momentum, the cloud spins faster as it contracts.

Collisions between particles flatten the cloud into a disk.

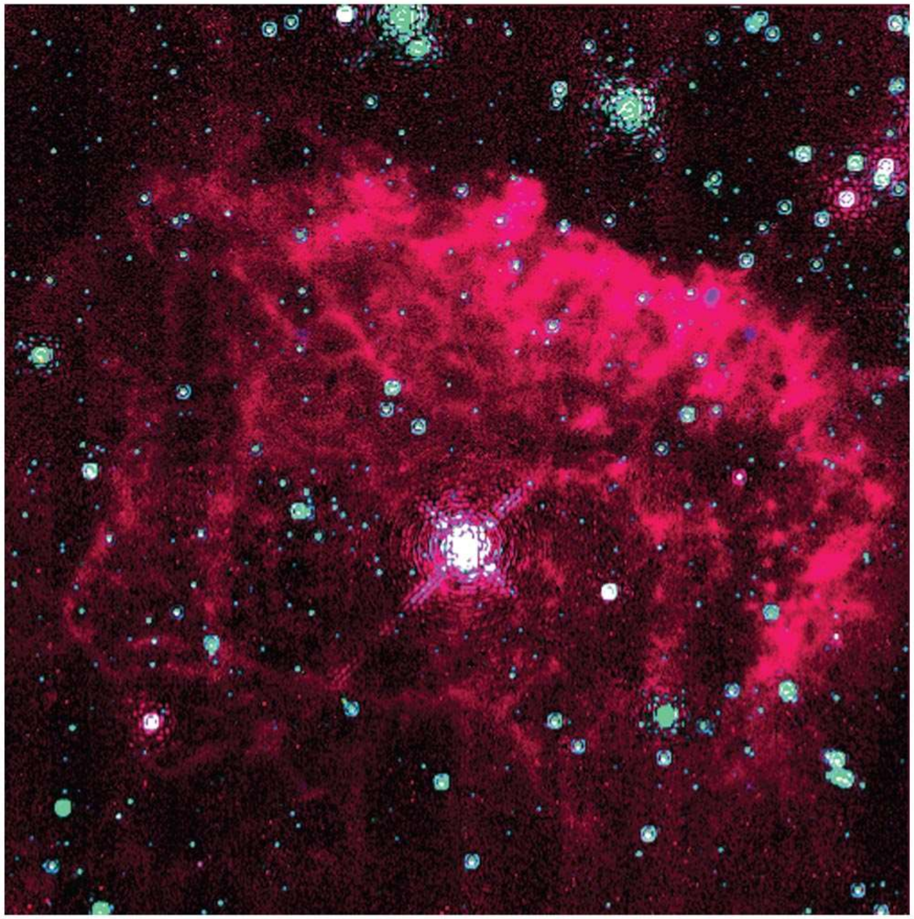
How Common are Massive Stars?



- Very massive stars are rare.
- In contrast, low-mass stars are very common.

→ What are the upper and lower limits to Star formation?

Upper Limit on a Star's Mass



- Photons exert a slight amount of pressure when they strike matter.
- Very massive stars are so luminous that the collective pressure of photons drives their matter into space.
- Models of stars suggest that radiation pressure limits how massive a star can be without blowing itself apart.
- Observations have not found stars more massive than about **300M_{Sun}. (RMC 136a1 315M_{Sun})**

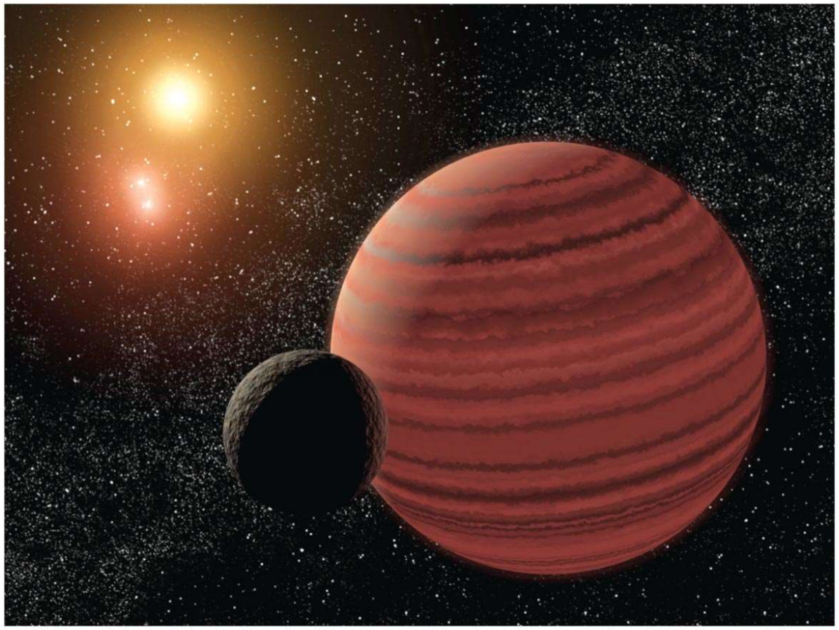
Lower Limit on a Star's Mass: Brown Dwarfs

- Fusion will not begin in a contracting cloud if some sort of force stops contraction before the core temperature rises above 10^7 K. (10 million K)
- Thermal pressure cannot stop contraction because the star is constantly losing thermal energy from its surface through radiation.

→ **Eventually this 'failed star' should keep contracting until it disappears completely? Or not?**

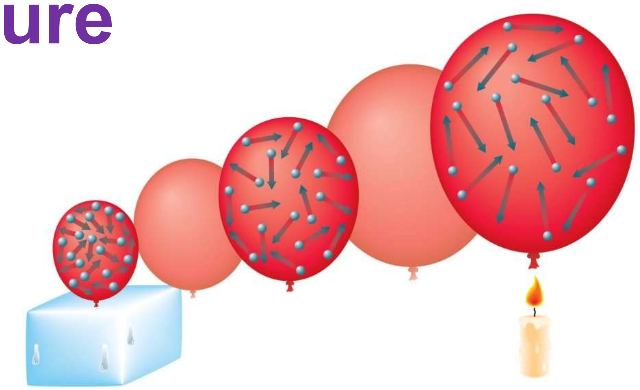
- Is there another form of pressure that can stop contraction?

→ yes, it's called ***degeneracy pressure***



a Artist's conception of a brown dwarf, orbited by a planet (to its left) in a system with multiple stars. The reddish color approximates how a brown dwarf would appear to human eyes. The bands are shown because we expect brown dwarfs to look more like giant jovian planets than stars.

The Difference Between Thermal Pressure and Degeneracy Pressure

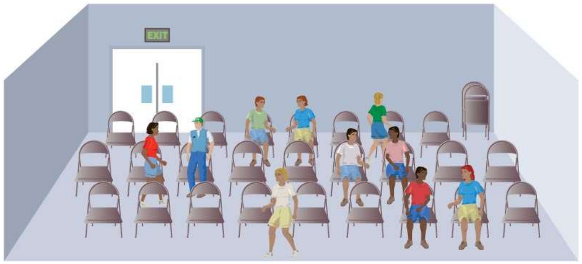


Thermal Pressure:

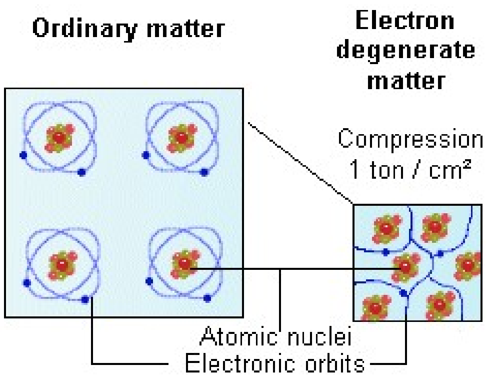
- Depends on heat content
- The main form of pressure in most stars

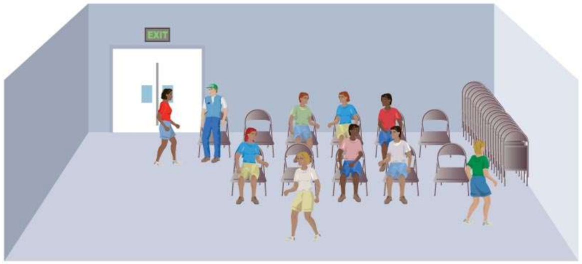
Degeneracy Pressure:

- Particles can't be in same state in same place
- Does not depend on heat content
- **For electrons:** Laws of quantum mechanics prohibit two electrons from occupying the same state in the same place.



a When there are many more available places (chairs) than particles (people), a particle is unlikely to try to occupy the same place as another particle. The only pressure comes from the temperature-related motion of the particles.

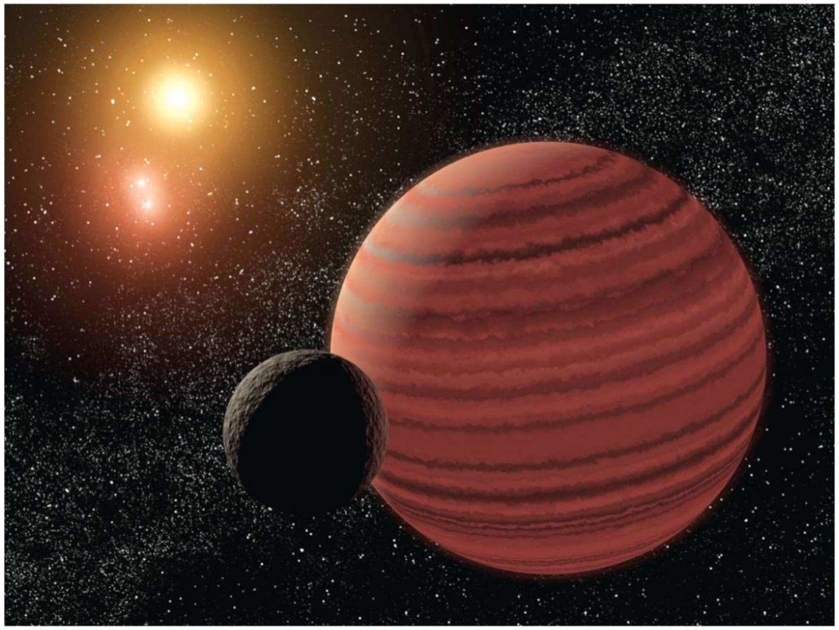




b When the number of particles (people) approaches the number of available places (chairs), finding an available place requires that the particles move faster than they would otherwise. The extra motion creates degeneracy pressure.

Lower Limit on a Star's Mass: Brown Dwarfs

- **Degeneracy pressure** halts the contraction of objects with **$<0.08M_{\text{Sun}}$** before the core temperature becomes hot enough for fusion.
- Starlike objects not massive enough to start fusion are **brown dwarfs**.
- A brown dwarf emits infrared light because of heat left over from contraction.
- Its luminosity gradually declines with time as it loses thermal energy.



a Artist's conception of a brown dwarf, orbited by a planet (to its left) in a system with multiple stars. The reddish color approximates how a brown dwarf would appear to human eyes. The bands are shown because we expect brown dwarfs to look more like giant jovian planets than stars.

End of Todays Lecture