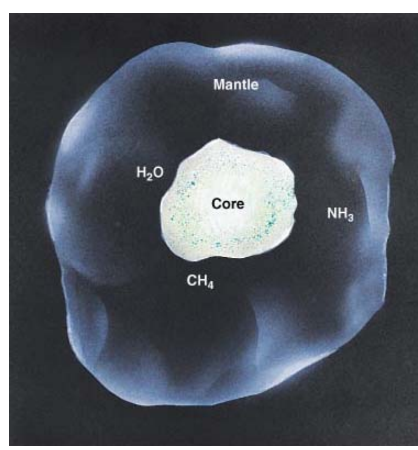
Star Formation: Interstellar Gas and Dust

- Space between stars is not empty after all.
- *Interstellar medium:*
  - Gas
  - Dust
  - Molecular clouds
- More concentrated in spiral arms of Galaxy
- Stars form from this material
- …and then eventually die and return gas back into interstellar medium.

Dust [19.4]

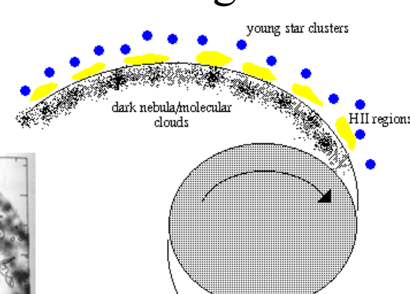
- Tiny grains
  - 10^{-8} to 10^{-7} m.
- Built up of molecules of most common elements after hydrogen and helium
  - Core: Silicates or Graphite (Si, O, C)
  - Mantle: C,N,O combined with H
- Absorb light
  - Absorb strongest in blue, less in red.
  - Blocks view through disk of our Galaxy
    - except in infrared
    - and (better yet) radio

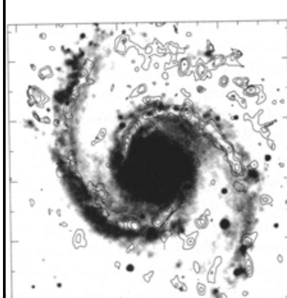


Molecular clouds

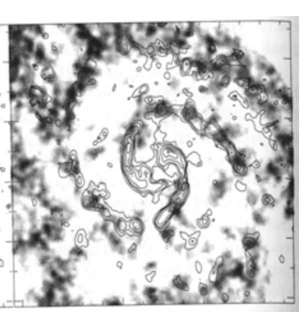
- Massive interstellar gas clouds
  - Up to ~10^5 $M_\odot$
  - 100’s of LY in diameter.
- High density by interstellar medium standards
  - Up to 10^5 atoms per cm^3
- Shielded from UV radiation by dust ➔ atoms are combined into molecules.
  - H_2 …and also H_2O, NH_3, CO plus much more complex molecules.
- Preferred place for stars to form.

Molecular clouds found on inner edges of spiral arms

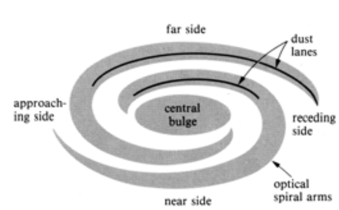




CO contours over red image

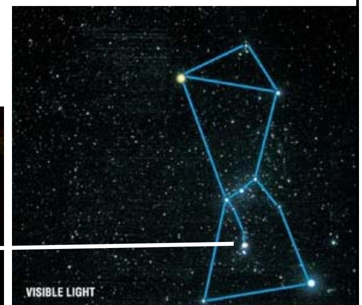


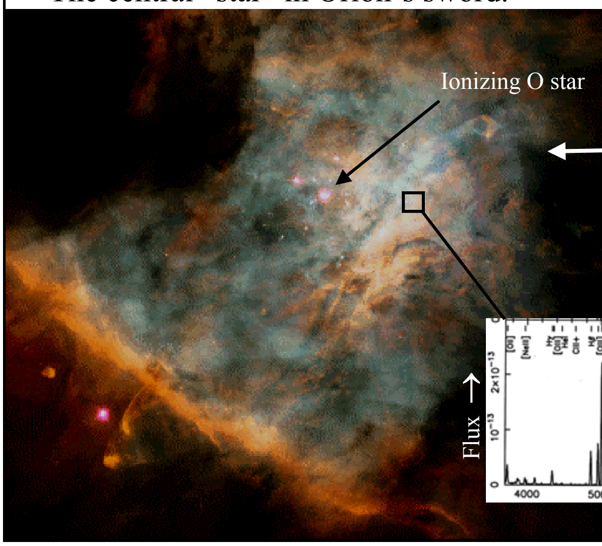
CO contours over 21 cm map



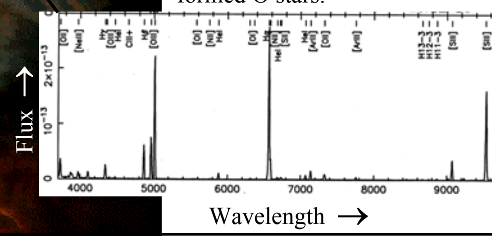
Example: The Orion Nebula

- 1500 LY away from us
- The central "star" in Orion's sword.

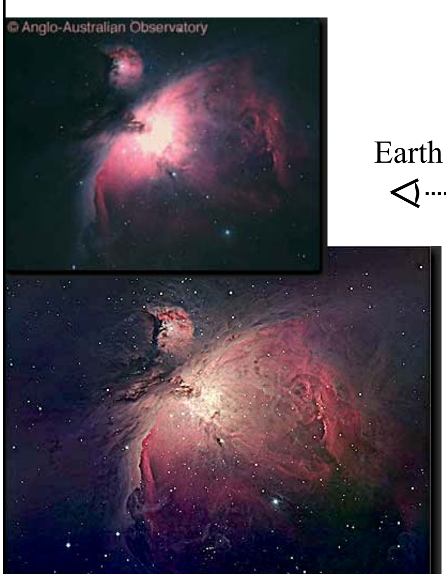


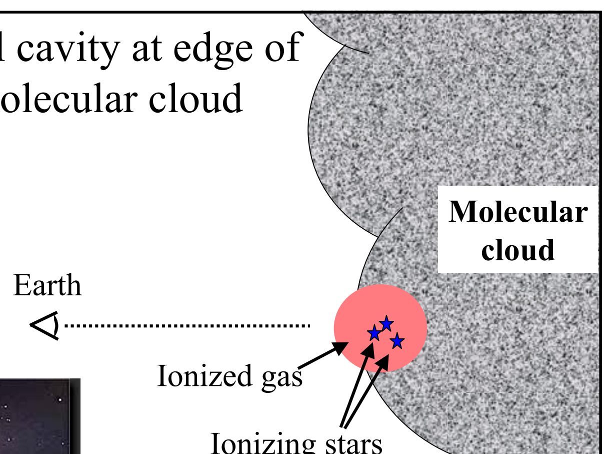


An "H II" region:
ionized gas excited by recently-formed O stars.



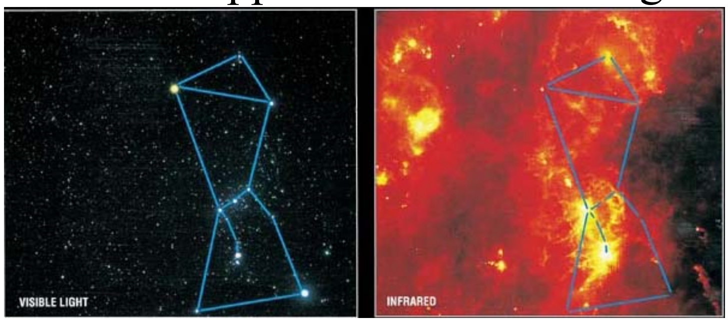
HII region is small cavity at edge of much bigger molecular cloud





- Ionized region has "blown out" of near side of dense cloud.
- Many more similar star-formation regions buried deep inside cloud.

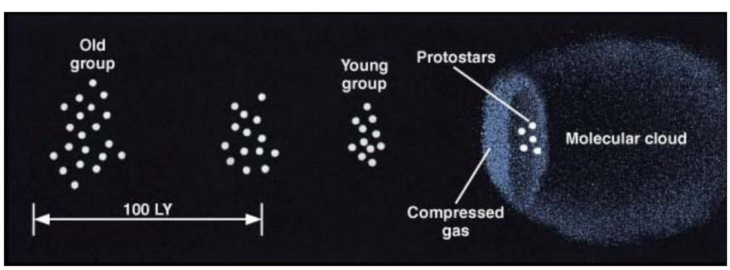
Full extent of star-formation region becomes apparent in infra-red light.



[Fig 20.3]

- 100 LY across
- 200,000 $M_{\odot}$
- Only a few of its stars close to the near edge can be seen in visible light.
  - Infrared light penetrates dust & shows many more stars.

Star formation waves in dense molecular clouds

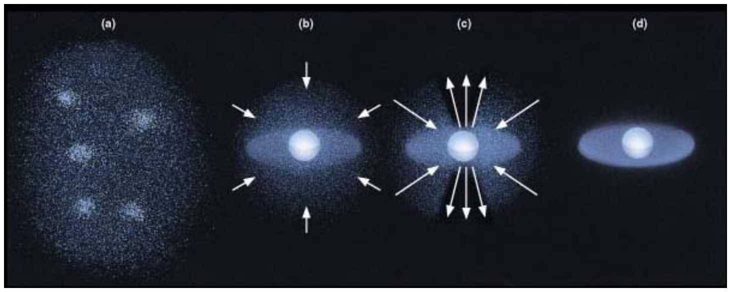


[Fig 20.7]

- Photons from very luminous O stars
  ➔ blows away gas + dust.
- ➔ Clusters emerge from dust shrouds.
- Compression of gas ➔ inward wave of star formation.

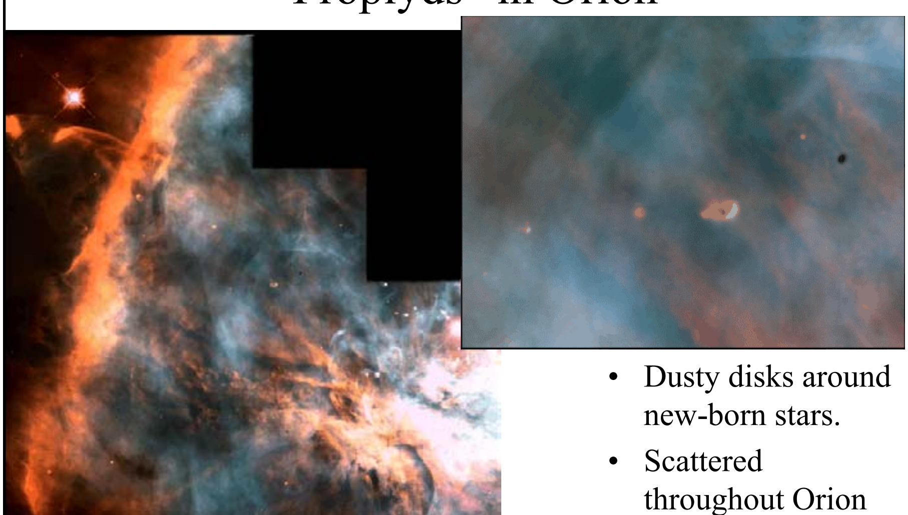
Collapse of proto-star

[Fig 20.8]



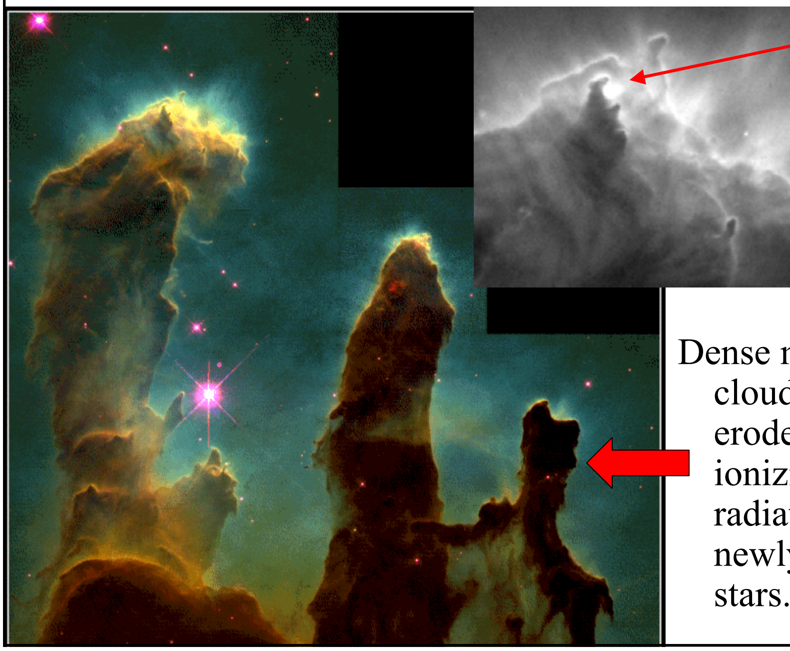
- Factor 100 density increase ➔ gas breaks up into star-sized chunks.
- Proto-stars then collapse due to gravitational self-attraction.
- Angular momentum ➔ disks.

“Proplyds” in Orion



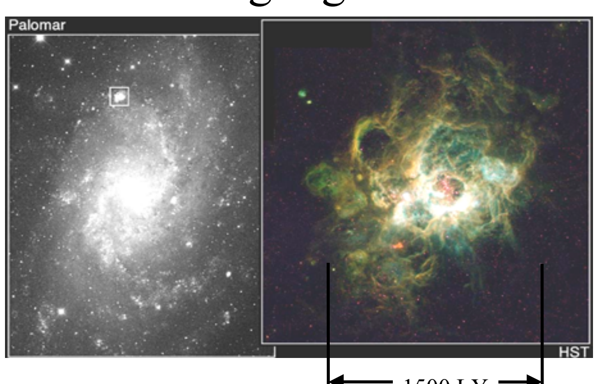
- Dusty disks around new-born stars.
- Scattered throughout Orion Nebula.

Another Example – M16 "Pillars of Creation"



Dense molecular clouds being eroded away by ionizing radiation from newly-formed stars.

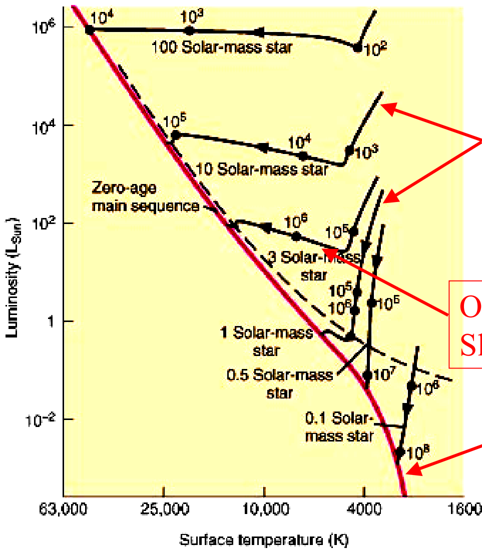
Star-forming region in M33



- NGC 604
  - Vast complex of molecular clouds & HII regions.
  - In outer spiral arms of the nearby galaxy M33.
  - Contains 200 O stars.

Theoretical models: Contraction to the main sequence

Protostars



Transparent, Freefall

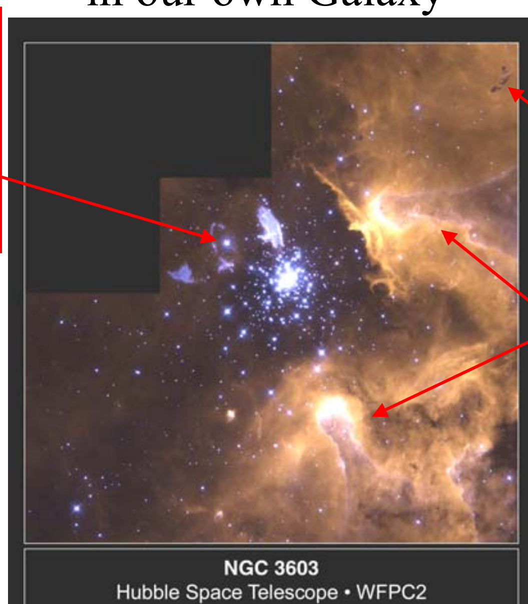
Opaque, Slow collapse

p-p reaction

[Fig. 20.12]

A recently formed cluster of stars in our own Galaxy

This more massive star has already gone through its life cycle and blown off its outer layers.



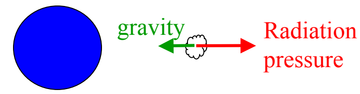
"Bok globules" still condensing into stars.

Dense fingers of molecular gas, just like in M16.

http://hubblesite.org/ then search for "NGC 3603"

Stellar masses range from ~ 200 $M_\odot$ to ~ 0.08$M_\odot$

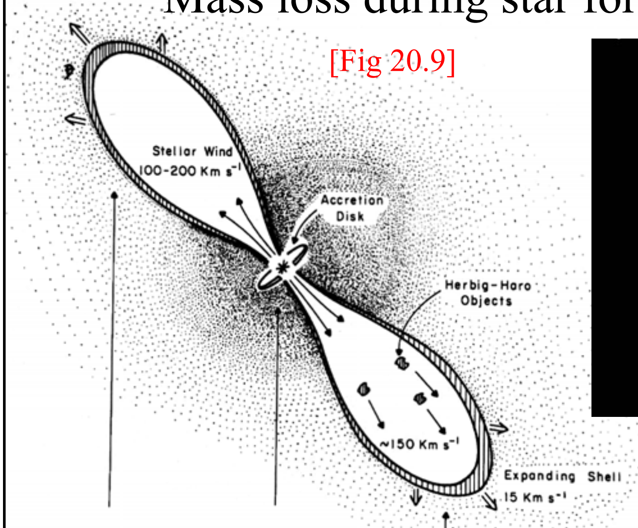
- What sets upper limit?
  - Radiation pressure:



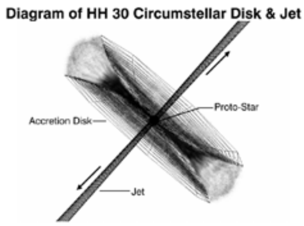
    - Photons carry momentum.
    - When atoms absorb photons they acquire this momentum.
    - Pushes atoms away from light source (star).
  - *Eddington limit.* Radiation pressure on gas exceeds gravitational attraction of star.
    - Blows away gas trying to fall onto forming star.
- What sets lower limit?
  - Collapsing gas cloud does not get hot enough in center to start p-p reaction.

Mass loss during star formation

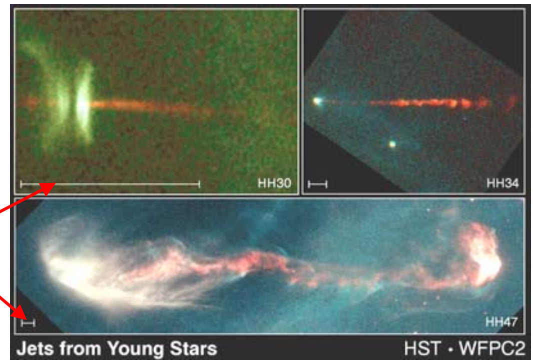
[Fig 20.9]



More Jets and Outflows from Protostars

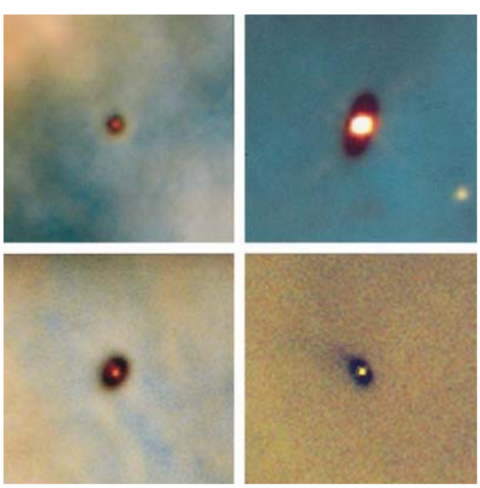


- "Accretion disk" around proto-star channels outflow along opposed jets.
- Star is continuing its gravitational contraction
- Still not burning H ➔ He.



1000 AU scale bars

Planets form from disks around young stars



From HST images of Orion

- These are all potential planetary systems.
- Disks formed due to angular momentum of gas that went into forming the star.

Known Planets Outside the Solar System

STAR	DISTANCE	SPECTRAL	MASS	SEM-MAJ.	PERIOD	ECC.
	(pc)	TYPE	(Jupiters)	AXIS (AU)	(days)	
HD 83443	43.5	K0 V	0.4	0.0	3.0	0.08
			0.2	0.2	29.8	0.42
HD 16141	35.9	G5 IV	0.2	0.4	75.8	0.28
HD 168746	43.1	G%	0.2	0.1	6.4	0.00
HD 46375	33.4	K! IV	0.2	0.0	3.0	0.00
HD 108147	38.6	F8/G0 V	0.3	0.1	10.9	0.56
HD 75289	28.9	G0V	0.4	0.0	3.5	0.05
51 Peg	15.4	G2IVa	0.5	0.1	4.2	0.00
BD -10 3166		G4 V	0.5	0.0	3.5	0.00
HD 6434	40.3	G3V	0.5	0.2	22.1	0.30
HD 187123	49.9	G5	0.5	0.0	3.1	0.03
HD 209458	47.0	G0V	0.7	0.0	3.5	0.00
ups And	13.5	F8V	0.7	0.1	4.6	0.03
			2.1	0.8	241.2	0.18
			4.6	2.5	1266.6	0.41
HD 192263	19.9	K2V	0.8	0.2	23.9	0.03
epsilon	3.0	K2V	0.9	3.3	2502.1	0.61
HD 38529	42.0	G4	0.8	0.1	14.4	0.28
55 Cnc	12.5	G8V	0.8	0.1	14.6	0.05
			> 5 ?	> 4	> 8 (y) ?	-
HD 121504	44.4	G2V	0.9	0.3	64.6	0.13
HD 37124	33.0	G4IV-V	1.0	0.6	155.0	0.19
HD 130322	30.0	K0III	1.1	0.1	10.7	0.05
rho CrB	17.4	G0Va	1.1	0.2	39.6	0.03
HD 52265	28.0	G0 V	1.1	0.5	119.0	0.29
HD 177830	59.0	K0	1.3	1.0	391.0	0.43
HD 217107	19.7	G8 IV	1.3	0.1	7.1	0.14
HD 210277	21.3	G0	1.3	1.1	437.0	0.45
16 CygB	21.6	G1.5Vb	1.5	1.7	804.0	0.67
HD 134987	25.0	G5V	1.6	0.8	260.0	0.25
HD 19994	22.4	F8V	2.0	1.3	454.0	0.20
Gliese 876	4.7	M4V	2.1	0.2	60.9	0.27
HD 92788	32.3	G5	3.8	0.9	340.0	0.36
HD 82943	27.5	G0	2.2	1.2	442.6 (y)	0.61
HR810	~ 15.5	G0V pecul.	2.3	0.9	320.1	0.16
47 Uma	14.1	G1V	2.4	2.1	3.0 (y)	0.10
HD 12661	37.0	K0	2.8	0.8	264.5	0.33
HD 169830	36.3	0	3.0	0.8	230.4	0.34

STAR	DISTANCE	SPECTRAL	MASS	SEM-MAJ.	PERIOD	ECC.
	(pc)	TYPE	(Jupiters)	AXIS (AU)	(days)	
14 Her	18.2	K0V	3.3	2.5	1619.0	0.35
GJ 3021	17.6	G6V	3.3	0.5	133.8	0.51
HD 195019	37.4	G3 IV-V	3.4	0.1	18.3	0.05
Gl 86	10.9	K1V	4.0	0.1	15.8	0.05
tau Boo	15.6	F6IV	3.9	0.0	3.3	0.02
HD 190228	62.1	G5IV	5.0	2.3	1127.0	0.43
HD 168443	37.9	G5	5.0	0.3	57.9	0.54
			~ 15	~ 2	1660.0	0.28
HD 222582	42.0	G5	5.4	1.4	576.0	0.71
HD 10697	30.0	G5IV	6.6	2.0	1083.0	0.12
70 Vir	18.1	G4V	6.6	0.4	116.6	0.40
HD 89744	40.0	F7 V	7.2	0.9	256.0	0.70
HD 114762	40.6	F9V	11.0	0.3	84.0	0.33
13 Jupiter mass limit						
HD 162020	16.3	K2 V	13.7	0.1	8.4	0.28
HD 110833	~17	K3V	17.0	~ 0.8	270.0	0.69
BD-04 782	-	K5V	21.0	~0.7	240.9	0.28
HD 112758	~ 16.5	K0V	35.0	~0.35	103.2	0.16
HD 98230		F8.5V	37.0	~0.06	4.0	0.00
HD 18445		K2V	39.0	~ 0.9	554.7	0.54
HD 29587	~45	G2V	40.0	~2.5	3.17 (y)	0.00
HD 140913	-	G0V	46.0	~ 0.54	147.9	0.61
HD 283750	~ 16.5	K2	50.0	~ 0.04	1.8	0.02
HD 89707	~ 25	G1V	54.0	-	198.3	0.95
HD 217580	~ 18	K4V	60.0	~ 1	454.7	0.52
Gl 229	6.7	M1/M2V	~ 40	~ 40	> ~200 (y)	-

- Lots of 'em
  - 108 planets now known
  - 94 systems
  - 12 multiple planet systems

Extrasolar Planets Catalog

see Extrasolar Planets Catalogue
http://www.obspm.fr/encycl/catalog.html

Some examples from previous list

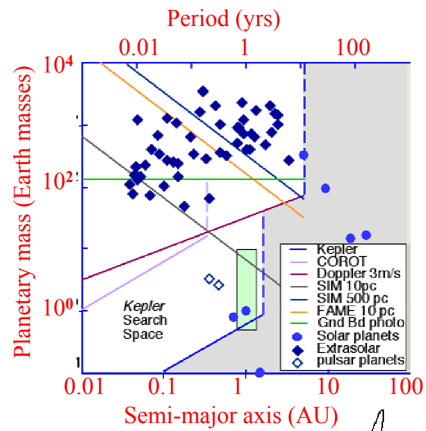
What is different from the Solar System?

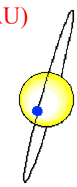
STAR	DISTANCE	SPECTRAL	MASS	SEM-MAJ.	PERIOD	ECC.
	(pc)	TYPE	(Jupiters)	AXIS (AU)	(days)	
HD 83443	43.5	K0 V	0.4	0.0	3.0	0.08
			0.2	0.2	29.8	0.42
HD 16141	35.9	G5 IV	0.2	0.4	75.8	0.28
HD 168746	43.1	G%	0.2	0.1	6.4	0.00
HD 46375	33.4	K! IV	0.2	0.0	3.0	0.00
HD 108147	38.6	F8/G0 V	0.3	0.1	10.9	0.56
HD 75289	28.9	G0V	0.4	0.0	3.5	0.05
51 Peg	15.4	G2IVa	0.5	0.1	4.2	0.00
BD -10 3166		G4 V	0.5	0.0	3.5	0.00
HD 6434	40.3	G3V	0.5	0.2	22.1	0.30
HD 187123	49.9	G5	0.5	0.0	3.1	0.03
HD 209458	47.0	G0V	0.7	0.0	3.5	0.00
ups And	13.5	F8V	0.7	0.1	4.6	0.03
			2.1	0.8	241.2	0.18
			4.6	2.5	1266.6	0.41
HD 192263	19.9	K2V	0.8	0.2	23.9	0.03

- All are massive planets (0.2 – a few Jupiters)
- All have small orbits
  - < 1 AU is typical (vs. 5 AU for Jupiter)
  - Many have large eccentricities

Search Methods Introduce *Selection Effects*

- Doppler shifts
  - Has found most extrasolar planets.
  - Need super-high accuracy.
- Astrometric wobble of the star
  - Use satellites ***(FAME, SIM)*.**
  - ➔slightly lower masses.
- Pulsars
  - Frequency of flashes “Doppler shifted”.
  - 3 Earth-sized planets around one pulsar.
  - Few places to search.
- Transit photometry
  - Planet blocks starlight.
  - Potentially most sensitive.
  - ***Kepler* , *COROT*** space missions proposed.





Binary Star Simulation

What types of planets are out there?

- Current search methods ➔ easiest to detect giant planets close to parent star.
  - ***But…why do giant planets exist at less than 1 AU?***

    – spiraling into the star, as a result of friction.
- Also - 3 Earth-sized planets circling pulsars
  - inhospitable environment.
  - These planets are thought to have formed *after* the supernova.
- Future space-based searches
  - Earth-sized planets in habitable zone around G stars like the Sun??????

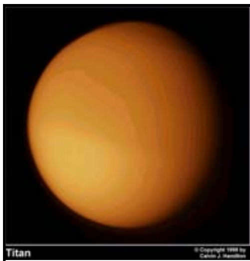
Life in the Solar System

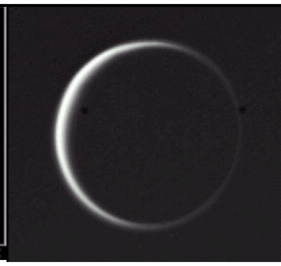
- Earth
  - Life formed in oceans.
  - Moved onto land only after photosynthesis transformed atmosphere from CO_2 to oxygen-rich.
- But not all life forms are powered by sunlight.
  - Black smokers – volcanic vents on ocean floor.

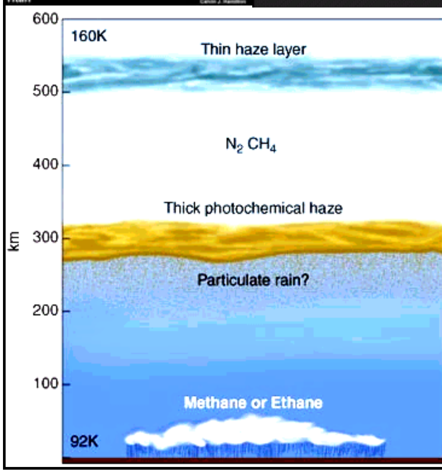
Life on Mars?

Meteorite from Mars.
- Formed on Mars 4.5 billion yrs ago.
- Ejected from Mars by meteor impact 15 million yrs ago.
- Eventually captured by Earth (!!)
- Found in Antarctica.

Possible discovery of organic compounds in Martian meteorites, and even a possible (micro) fossil.
- *Unclear!* Considerable skepticism among many scientists.
- Extraordinary claims require extraordinary proof.





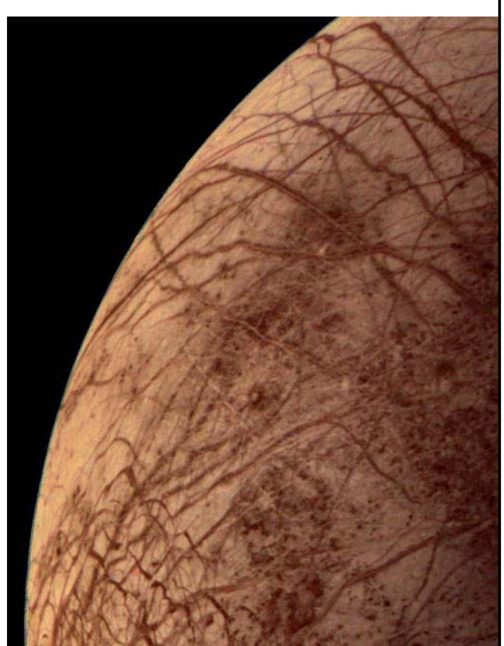


Titan (moon of Saturn) has Earth-like atmosphere

- Density about same as Earth's
  - 1.6 bars at surface
- Primarily N_2, but also:
  - carbon monoxide (CO)
  - methane (CH_4)
  - ethane (C_2H_6)
  - propane (C_3H_8)
  - hydrogen cyanide (HCN)
    - a building block of DNA
  - C_2N_2, HC_3N
- Thick photochemical smog obscures surface.
- Surface temp = -180º C

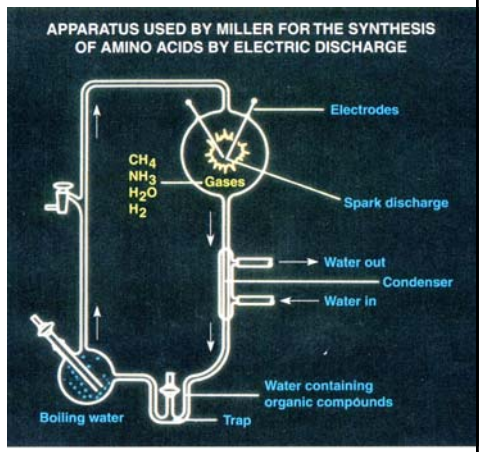
Europa (moon of Jupiter)

- Covered by layer of water ice.
  - Rocky core ➔ minerals.
  - "Pack ice" on top of an ocean.
  - Water must be warmed by heat from Europa's interior.
  - ➔ energy source for life???



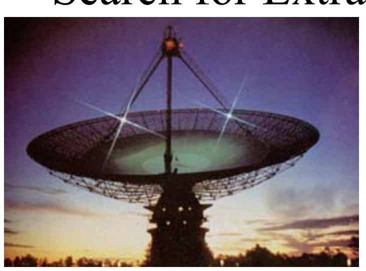
How hard is it to form life?

- Life formed very rapidly on Earth
  - Oldest fossils 4 billion yrs old
  - Earth only 4.5 billion yrs old
  - ➔ relatively easy to form life.
- Primitive atmosphere experiments in early 1950's:
  - Simulated Earth's original atmosphere + lightning.
  - Amino acids formed.
- Organic molecules found in:
  - Atmosphere of Jupiter
  - Comets
  - Giant molecular clouds
- Amino acids found in meteorites.

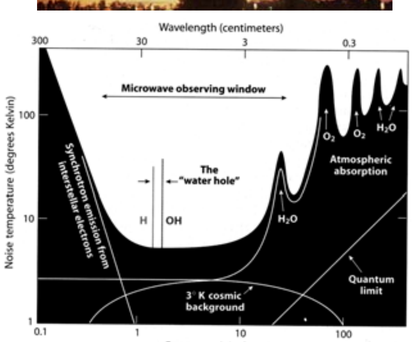


If Life is easily formed, then it should be found in many places.

SETI
Search for ExtraTerrestrial Intelligence



- Listen for radio transmissions from other civilizations..



- But what wavelengths should we search at?
  - As a guess: Search in wavelength band between lowest transitions of H, OH .
  - High transparency.

Is there life out outside the Solar System?

- Drake Equation

Number of observable civilizations = $N = R\ f_p\ n_e\ f_l\ f_c\ L$

	Parameter
R	rate at which stars form in Milky Way
f_p	fraction wi
n_e	average # e
f_l	fraction wi
f_c	fraction ca
L	average lifetime of communicating civilization

$$\frac{\text{Number}}{\text{time}} \times \text{Lifetime} = \text{Number at a given time}$$

$$\frac{1\ \text{ball}}{\text{sec}} \times 20\ \text{sec} = 20\ \text{balls in air}$$

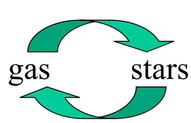
Drake equation: 1961
40 years later: no detections.

Number of observable civilizations = $N = R\ f_p\ n_e\ f_l\ f_c\ L$

	Parameter	Best estimate
R	rate at which stars form in Milky Way	~ 1 per year
f_p	fraction with planets	lots
n_e	average # earth-like planets per solar system	small???
f_l	fraction with life	high??
f_c	fraction capable of interstellar radio communication	???
L	average lifetime of communicating civilization	???

The galaxy

- Originally all gas
- Now ~10^{11} stars similar to our sun.
- Stars are borne, evolve, then die.
- Material processed through stars.
  - Galactic ecology



- This is source of all chemical elements

except Hydrogen (H)
Helium (He)
Lithium (Li)

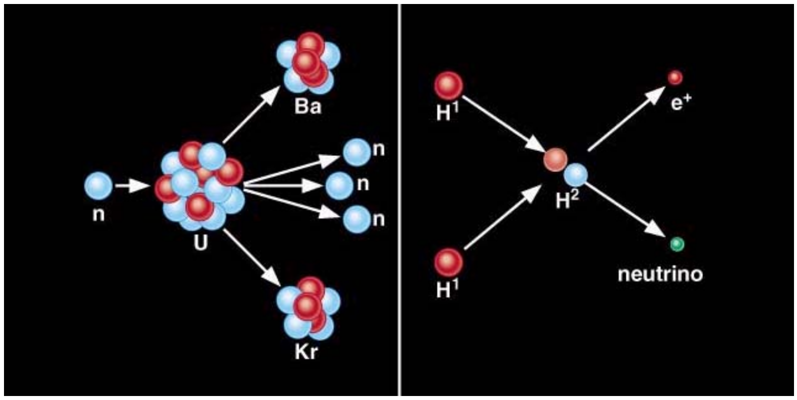
made in "big bang"

The Evolution of Stars & The Production of the Chemical Elements

Summary of Chapters [16→22].

- Leaves out *how* we know.
- Just *what* we know.

Fission vs Fusion

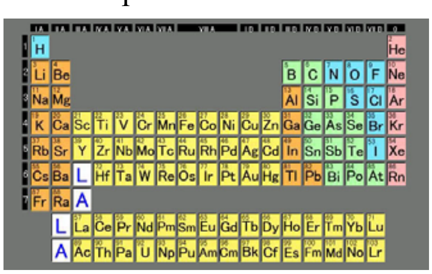


Fission: elements heavier than iron, breaking up to reach lower energy state per nucleon.

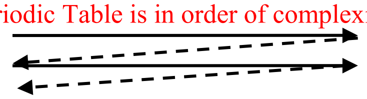
Fusion: elements lighter than iron, combining to reach lower energy state per nucleon.

Nucleosynthesis: where we came from.

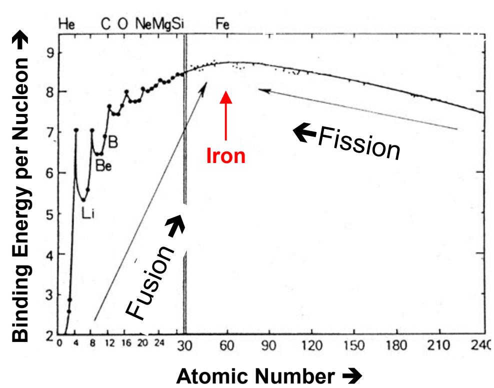
- H, He, Li are only elements formed in initial formation of universe.
  - simplest stable combinations of protons, neutrons and electrons



Periodic Table is in order of complexity



Element	Protons	Neutrons	Total
H	1	0	1
He	2	2	4
Li	3	4	7
C	6	6	12
N	7	7	14
O	8	8	16
Fe	26	30	56



Fusion in stars → increasingly more complicated, but more stable nuclei.

- Up until iron (Fe).

What is inside the Sun?

- Measure
  - Luminosity
  - Mass
  - Diameter
  - Chemical composition

- Infer (from our knowledge of Physics)
  - Internal structure

What is inside other stars?

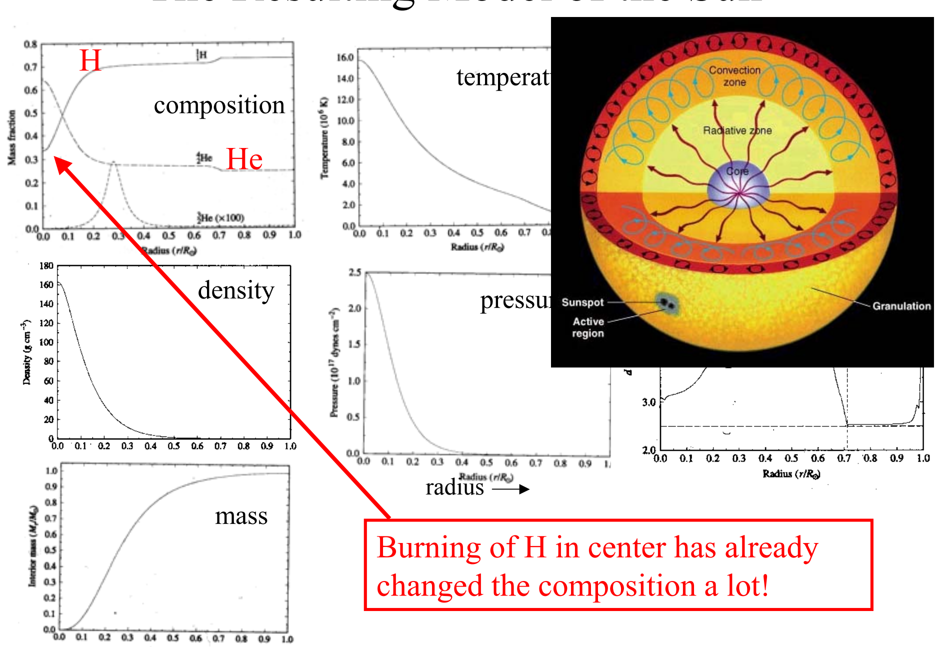
- Measure
  - Luminosity
  - Mass
  - Surface temperature
  - Chemical composition

Calculate diameter

From Luminosity and Temperature

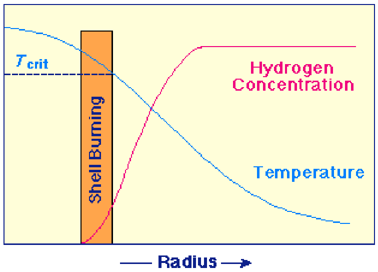
- Infer
  - Internal structure

The Resulting Model of the Sun



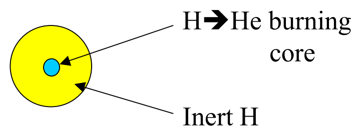
Burning of H in center has already changed the composition a lot!

Eventually, H burns outward in a shell

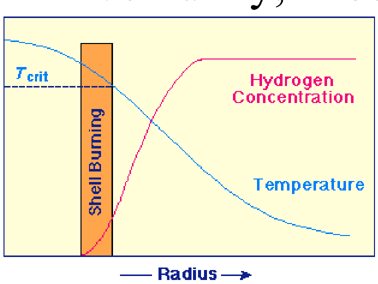


- Heat source moves closer to surface.
- Layers below surface swell up.
- Star becomes larger
- Surface becomes cooler

➔ *Red giant.*



Eventually, H burns outward in a shell



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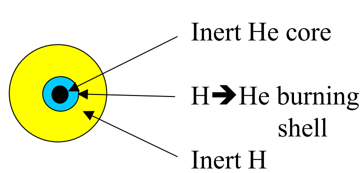

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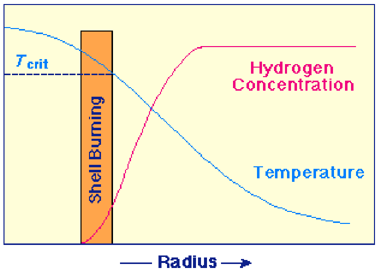

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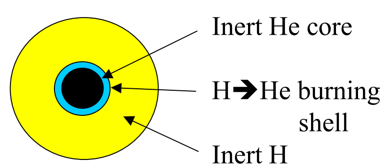

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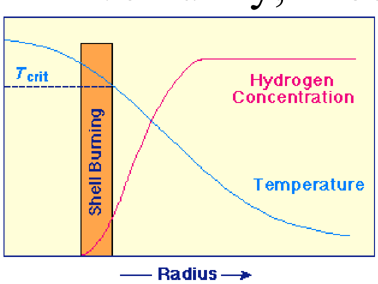

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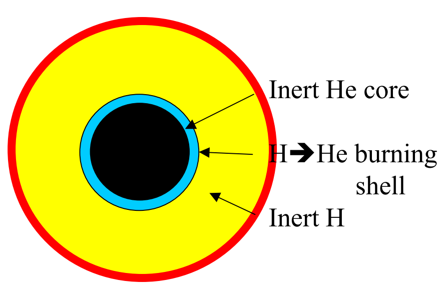


The Sun currently is neither contracting nor expanding:

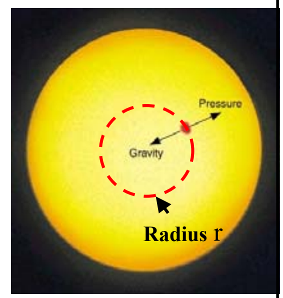
- Pressure support from below = gravitational attraction towards center
- But following exhaustion of H fuel in center:

  No further nuclear burning

  ➔ Temperature drops

  ➔ Pressure drops

  ➔ Core contracts



[Fig 15.7]

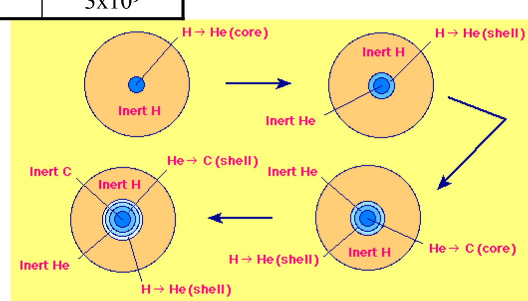
- Core contraction releases gravitational energy
  - So center heats up
  - But never enough to maintain hydrostatic equilibrium.

What we need are: *New sources of fuel*

Reaction	Min. Temp.
4 ^{1}H ➔ ^{4}He	10^{7} °K
3 ^{4}He ➔ ^{12}C	2×10^{8}
^{12}C + ^{4}He ➔ ^{16}O, Ne, Na, Mg	8×10^{8}
Ne ➔ O, Mg	1.5×10^{9}
O ➔ Mg, S	2×10^{9}
Si ➔Fe peak	3×10^{9}

Triple-alpha process

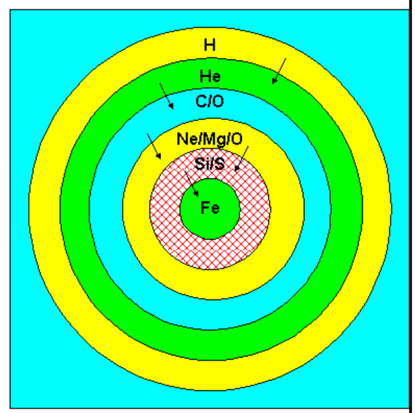
- Contraction heats center
- Helium starts to burn.



Then…nuclear burning in successive shells

Reaction	Min. Temp.
4 $^{1}H \rightarrow {}^{4}He$	10^{7} ° K
3 $^{4}He \rightarrow {}^{12}C$	$2x10^{8}$
$^{12}C + {}^{4}He \rightarrow {}^{16}O$, Ne, Na, Mg	$8x10^{8}$
Ne $\rightarrow$ O, Mg	$1.5x10^{9}$
O $\rightarrow$ Mg, S	$2x10^{9}$
Si $\rightarrow$ Fe peak	$3x10^{9}$

- "Onion skin" model
  - Central core is iron
  - Outer layers correspond to each previous step in nuclear burning chain.



Lifetime for burning 4H $\rightarrow$ ^{4}He
(called "main sequence" lifetime)

Spectral Type	Surface Temp.	Mass ($M_{\odot}$)	Lifetime (yrs)
O5	40,000	40	10^{6}
B0	28,000	16	10^{7}
A0	10,000	3.3	$5x10^{8}$
F0	7,500	1.7	$3x10^{9}$
G0	6,000	1.1	$9x10^{9}$
K0	5,000	0.8	10^{10}
M0	3,000	0.4	$2x10^{11}$

HR – The Movie

Lifetimes of stars

Then… much faster evolution through:

- Red giant (4H $\rightarrow$ ^{4}He in shell)… takes only 10% as long as main seq. life.
- Helium flash ($3^{4}He \rightarrow {}^{12}C$)
- He shell burning.
- C $\rightarrow$ heavier elements.

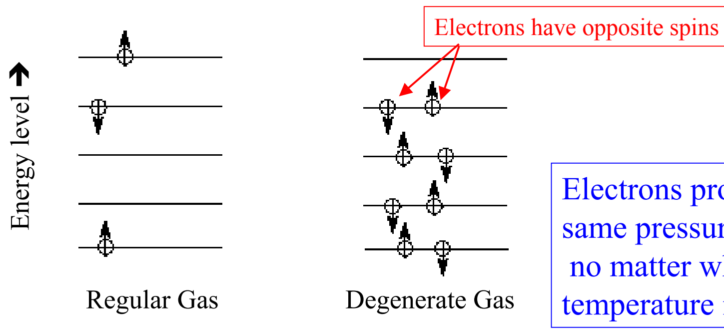
What stars do

- Gravity ➔ Center of star always trying to contract and become more dense.

- Nuclear burning interrupts this from time to time
  - High temperature ➔ high pressure
  - *Pressure* is what halts gravitational contraction.

Sufficiently high density ➔ Electron degeneracy.

- Pauli exclusion principle ➔ cannot have two electrons in same place with exactly same energy.
- ➔ electrons produce pressure.



Electrons produce same pressure, no matter what the temperature is.

- So we can have high pressure without nuclear burning.

Possible ending #1: a white dwarf

- For mass < $1.4M_\odot$
  - Pressure from electron degeneracy is sufficient to support star

➔ ***white dwarf***

- A giant crystal-like lattice of nuclei.
- Electrons conduct heat outwards to surface.
- Surface is steadily-cooling black body.

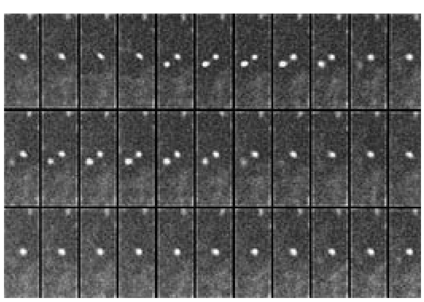
Possible ending #2: a neutron star

If degenerate electron pressure *cannot* support the star:

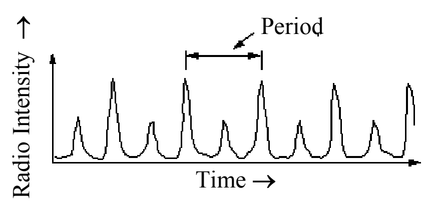
$e^- + p^+ \rightarrow n + \text{neutrinos}$

- Still denser state of matter than electron degeneracy.
  - Sun: 1,000,000 km diameter
  - White dwarf: 10,000 km (~ same diameter as Earth)
  - Neutron star: 20 km
- Degenerate pressure of neutrons can support stars up to $3M_\odot$

Pulsars: observations of neutron stars

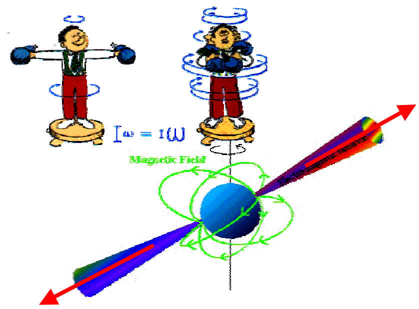


Time series in visible light.
0.033 sec pulsar is next to a star
of constant brightness.



- Originally found repeating radio bursts
- Coming from some distant point in space.
  - Dozens now known.
  - Pulses repeat with periods ranging from 0.001 to 10 sec.
- Many can also be detected in visible light.

The Pulsar "Lighthouse"



Beam sweeps past observer either once or twice per spin

Chandra - X-Ray Sources - Pulsar

Circumference of spinning star $= 2\pi R$.

- Energy is emitted by charged particles accelerated along poles of magnetic field.
- Magnetic field is tilted relative to spin axis.
- Collapsed star spins rapidly.
  - conservation of angular momentum.
- What is diameter?
  - Star's surface cannot spin faster than speed of light.
  - $2\pi R / t < c$
    - $\Rightarrow R < ct/(2\pi)$
  - 0.001 sec period $\Rightarrow R < 50$ km
- It *has* to be a neutron star.

Possible ending #3: a black hole

- Degenerate pressure of neutrons can support stars only up to $3M_\odot$
- For $M > 3M_\odot$: Further collapse $\Rightarrow$ black hole
  - Mass is so concentrated that light cannot escape.
    - One way to think about it:
      - $v_{escape} = \sqrt{2GM/R}$ becomes greater than speed of light.
      - So photons can't escape.
  - Black holes now known on three size scales:
    - $M \sim$ a few $M_\odot$ (Single star. $R_{Schwarzschild} = 9$ km)
    - $M \sim 10^5 M_\odot$ (recently found in 2 globular clusters)
    - $M \sim 10^8 M_\odot$ (Quasar in center of a galaxy)

- What is the state of the mass inside the black hole???

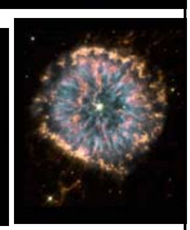
How do stars get from here to there?

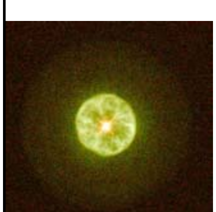
Here: Evolution through nuclear burning.	
$M_{initial} > 3M_\odot$	Nuclear burning all the way to iron.
$M_{initial} < 3M_\odot$	Nuclear burning shuts off after He-flash.

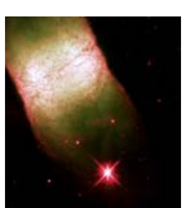
There: Final state.	
$M_{final} > 3M_\odot$	Black hole.
$1.4 < M_{final} < 3M_\odot$	Neutron star.
$M_{final} < 1.4M_\odot$	White dwarf.

Hubble images of Planetary Nebulae

These are former Red Giants, blowing away outer 25% of their mass because of intense energy production in middle layers of star.

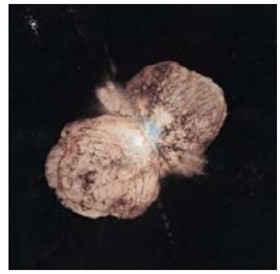


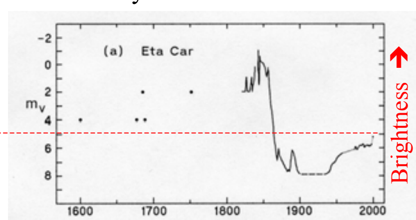




Very massive stars also expel material late in life

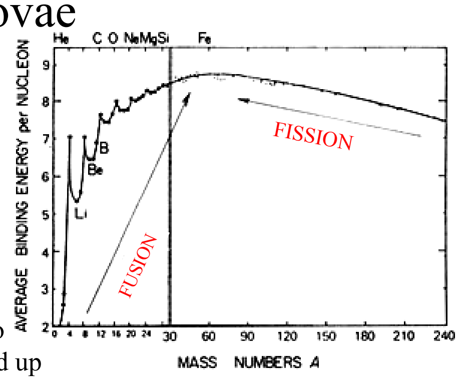
- Eta Carinae
  - 150 $M_\odot$
  - 4 million $L_\odot$
  - Highly variable in luminosity.
  - This material ejected in 1843.
    - Major brightening recorded.
    - Ejected 3 $M_\odot$
    - 2nd brightest star in sky at that time.

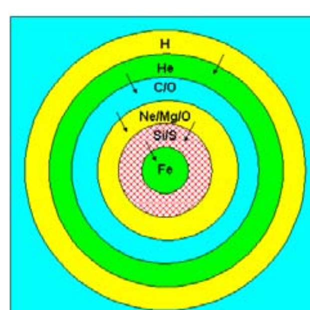




Supernovae

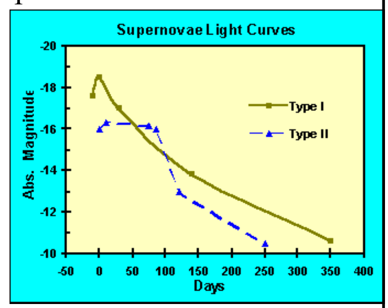
- Stars more massive than 7-8 $M_\odot$ cannot "gracefully" lose mass and become white dwarfs.
- Massive stars end up with iron cores.
- No further nuclear burning possible
  - Combining iron into heavier elements soaks up energy.
- Outer layers of star gradually contract onto core which becomes too massive to be held up by degenerate electron pressure
  - $e^- + p \rightarrow n$
  - Sudden core collapse: 10^4 km → 20 km
  - Then core rebounds
  - Outer layers fall in, then get hit by rebounding core.



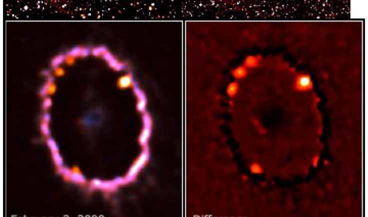


Kapow!

- Explosion releases huge kinetic energy
  - ➔ heating ➔ lots of photons
- Luminosity in photons temporarily exceeds that of whole galaxy full (10^{11}) of stars.
- But far greater luminosity in neutrinos
  - $e^- + p$ ➔ n + neutrino

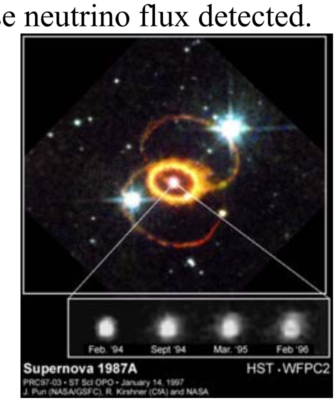


Supernova 1987A



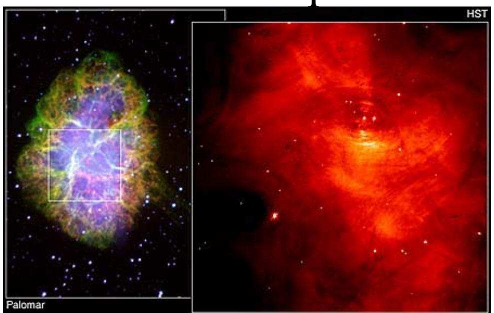
- Exploded in Large Magellanic Cloud
  - Small spiral galaxy that orbits our own Galaxy.
- Caught in act of exploding and intensively studied.
- Intense neutrino flux detected.

Pre-existing circumstellar ring lit up first by photons from SN, now by blast wave from SN.

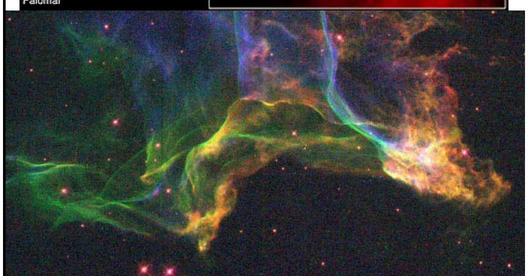


Supernova remnants

We expect one supernova in Milky Way every 25-100 yrs.



Crab Nebula.
1054 AD.
Ripples are due to energy being dumped into gas by beam from pulsar.



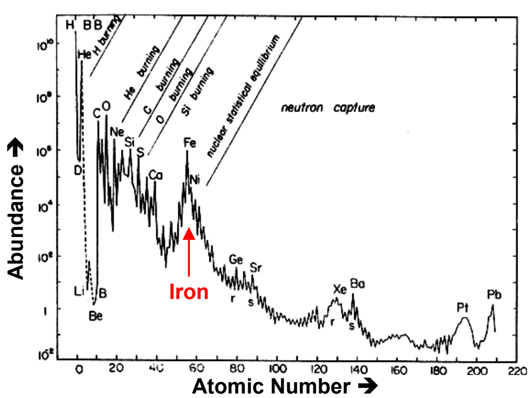
Cygnus Loop
20,000 yrs old.
2500 LY away.

IC 443
8000 yrs old

History of our Galaxy: Traced through Nucleosynthesis

- H ➔ He
  - main sequence, red giants
  - supplements primordial He.
- He ➔ C, N
  - red giants, helium flash, etc.
- C, N ➔ Fe
  - cores of massive stars.
- Fe ➔ heavier elements (U, etc).
  - supernova explosions.
  - bombardment by neutrons.

- Recycling back into interstellar gas
  - Planetary nebula shells
  - Other mild-mannered mass loss
  - Supernovae



Chemical history of our galaxy

- *Chemical enrichment*
  The buildup of the heavy elements through nucleosynthesis.
- Galaxy started with just H, He, Li
- H ➔ He ➔ C ➔ O burning has steadily built up carbon, oxygen.
- Elements like iron built up (somewhat) more recently.