

# "The Planets"

Astro/EPS C12 (CCN 17045 or 32505)

Dr. Michael H. Wong



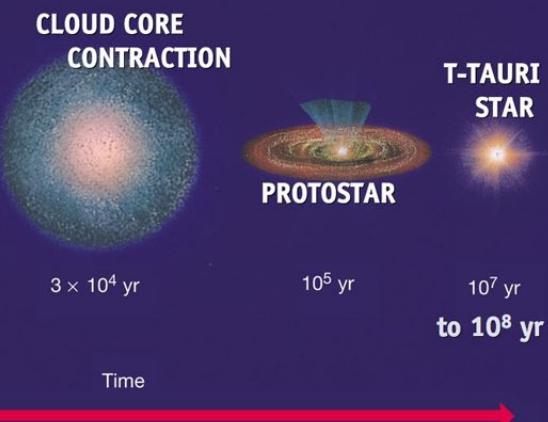
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[astro.berkeley.edu/~mikewong/C12.html](http://astro.berkeley.edu/~mikewong/C12.html)

LEC: 2 LeConte TWTh, 2:40–5:00pm  
Office Hours: 419 Campbell Hall,  
Mon 3–4 and Tue 5–6

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## STARFORMATION

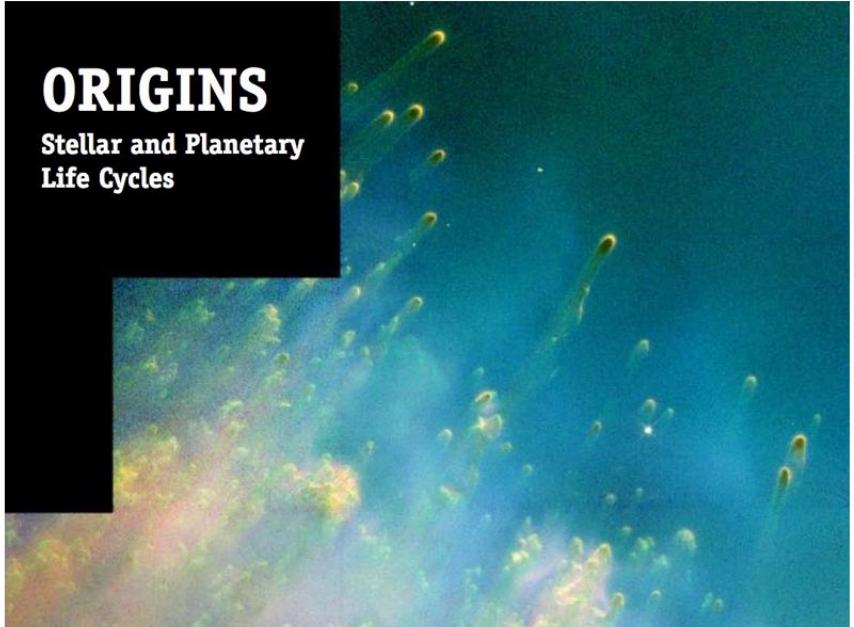
CLOUD COLLAPSE  
AND  
FRAGMENTATION



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## ORIGINS

Stellar and Planetary  
Life Cycles



## INTERSTELLAR MEDIUM

### INTERSTELLAR MEDIUM

- ~1 H atom per cm<sup>3</sup>

### H I REGIONS

- can sometimes contain denser MOLECULAR CLOUDS with H<sub>2</sub> molecules

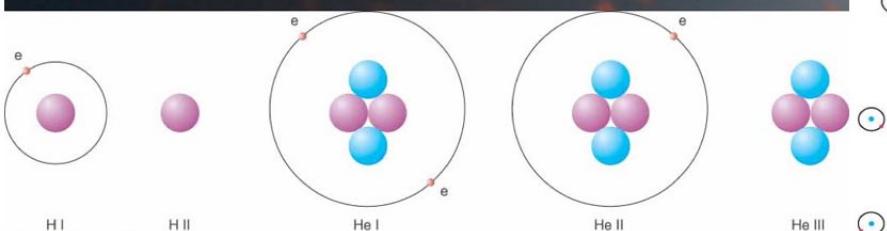
### H II REGIONS

- ionized hydrogen
- energy from hot stars causes ionization
- emission nebulae are found here

### DUST

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# ATOMS and their IONS



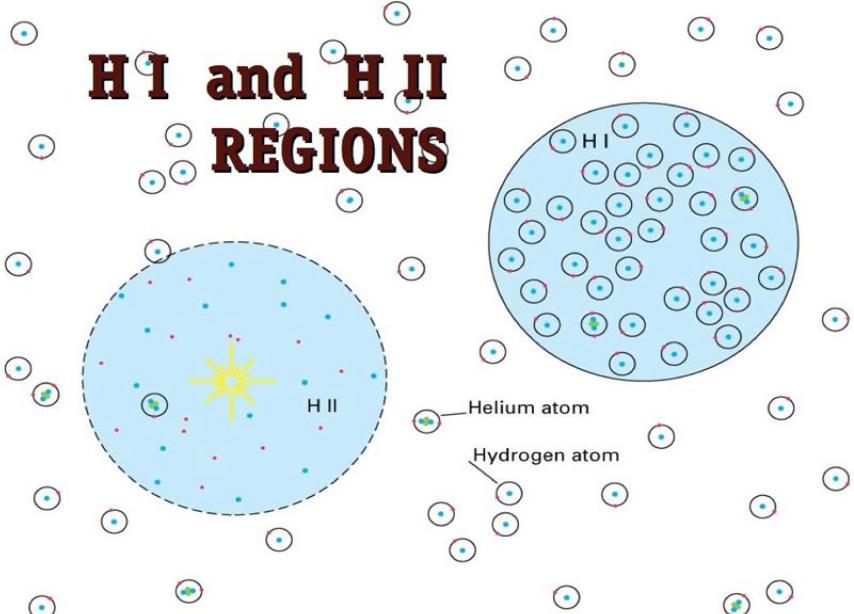
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- ions are formed by removing or adding electrons to the neutral atom

- ions are charged particles
- UV radiation is strong enough to ionize

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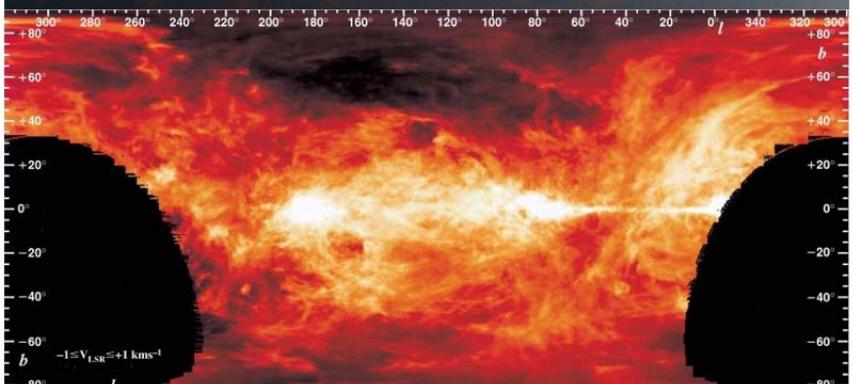
## H I and H II REGIONS



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## H I REGIONS

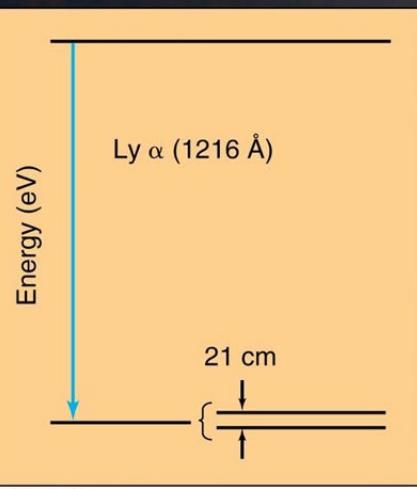
- 21-cm emission from H I



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## 21-cm H EMISSION

- transition energy very small
- spin-state transition

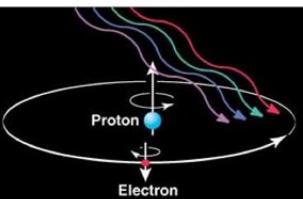
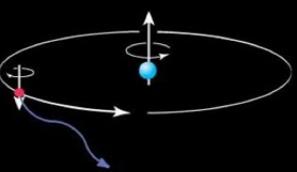
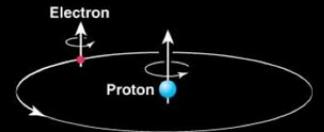


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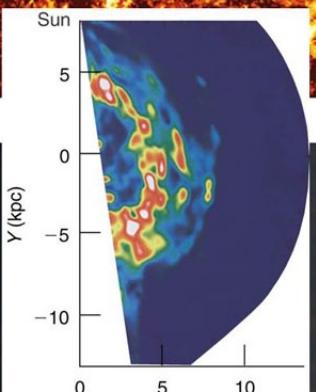
# SPIN-STATE TRANSITION



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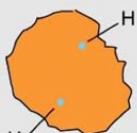
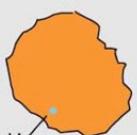
## CO: TRACER MOLECULE



• CO reveals locations of dust and  $H_2$

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Dust grain



5000 years later

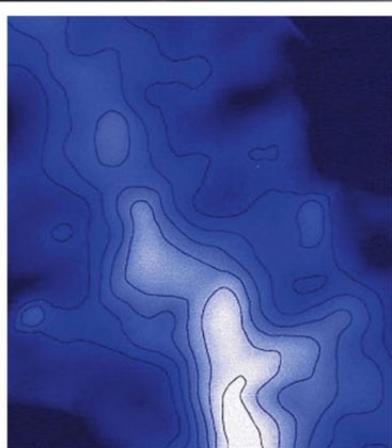
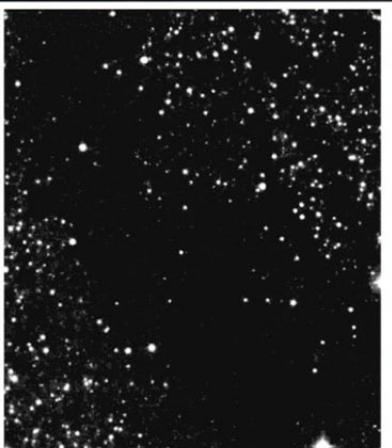


## MOLECULES AND DUST GO TOGETHER

- $H_2$  can form on dust grains
- dust shields other molecules from UV in space that would disassociate the molecules

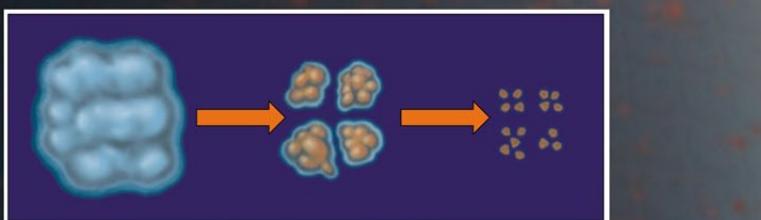
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## INTERSTELLAR CLOUDS

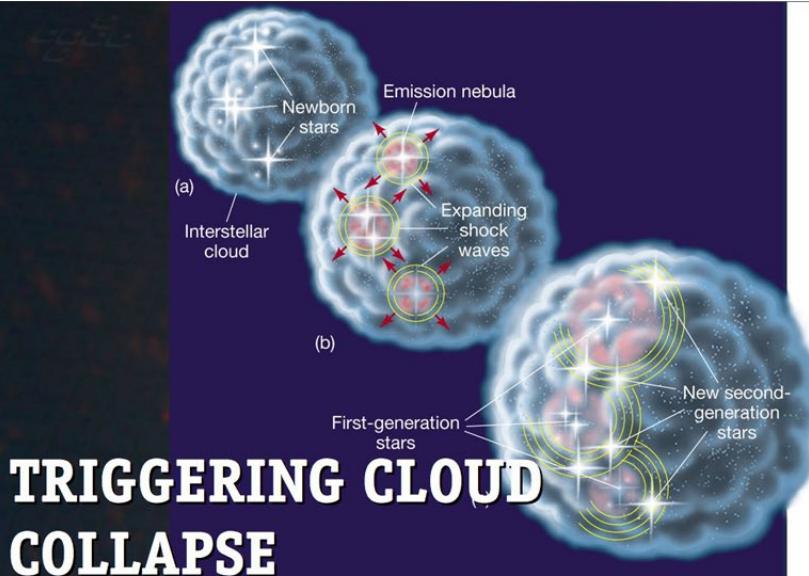


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## INTERSTELLAR CLOUDS



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## TRIGGERING CLOUD COLLAPSE

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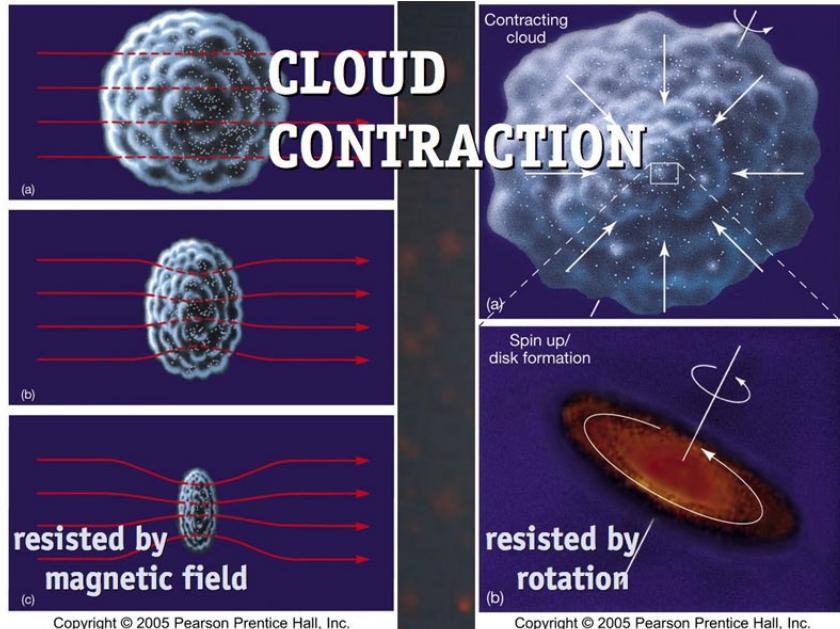
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## DENSE DUST CLOUDS



IC 2944

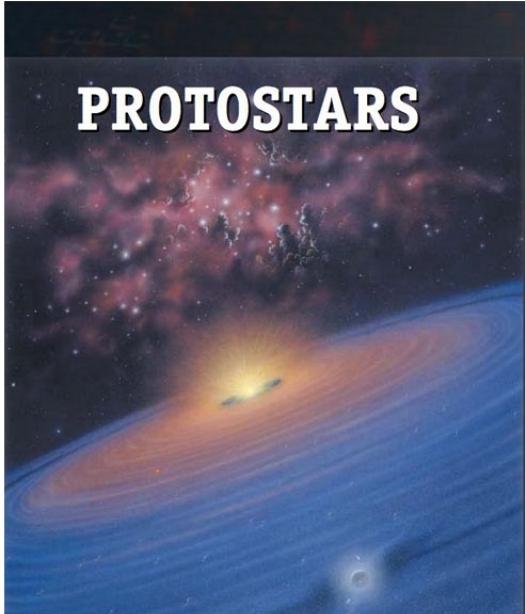
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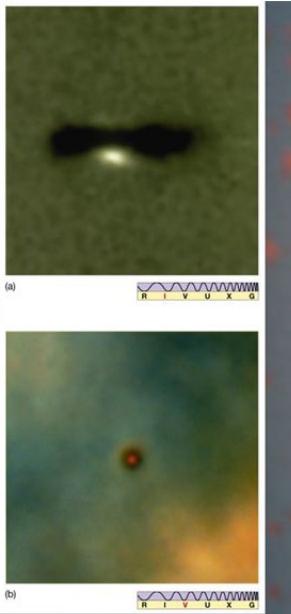
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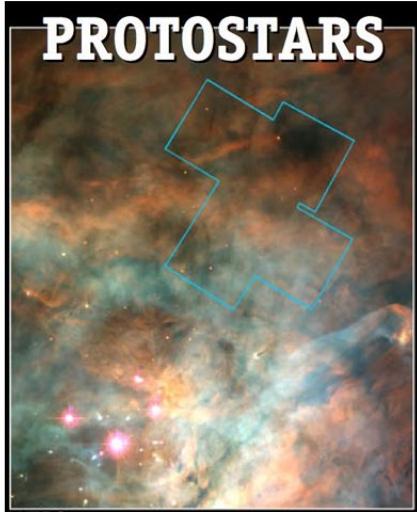
# PROTOSTARS



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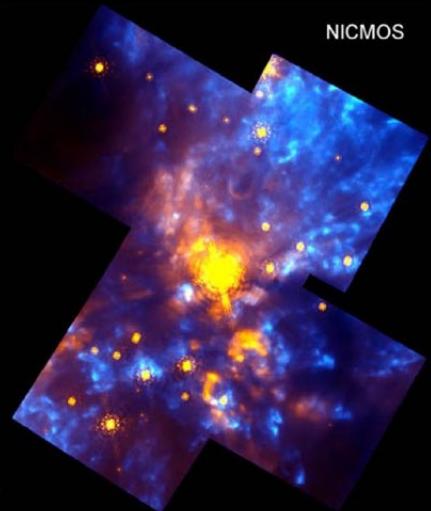
# PROTOSTARS



Orion Nebula • OMC-1 Region

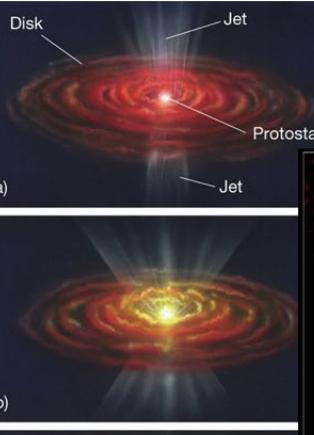
PRC97-13 • ST Scl OPO • May 12, 1997

R. Thompson (Univ. Arizona), S. Stolovy (Univ. Arizona), C.R. O'Dell (Rice Univ.) and NASA

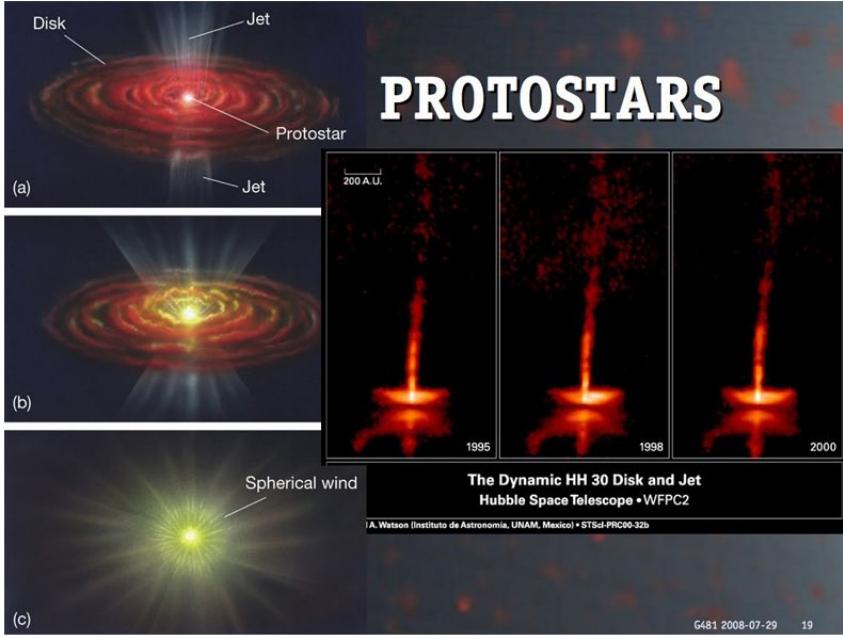


Hubble Space Telescope

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# PROTOSTARS

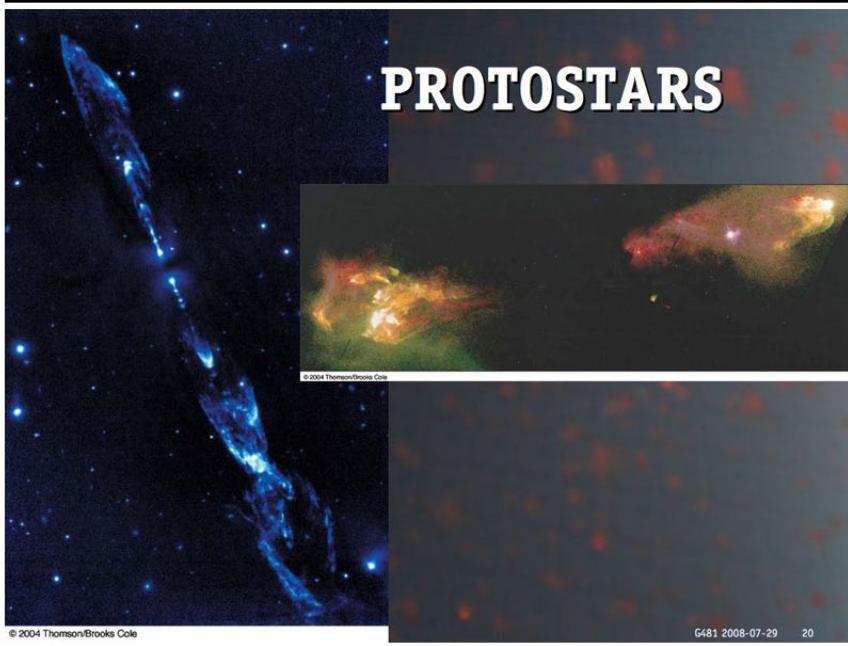


The Dynamic HH 30 Disk and Jet  
Hubble Space Telescope • WFPC2

A. Watson (Instituto de Astronomia, UNAM, Mexico) • STScI-PRC00-32b

(c)

# PROTOSTARS

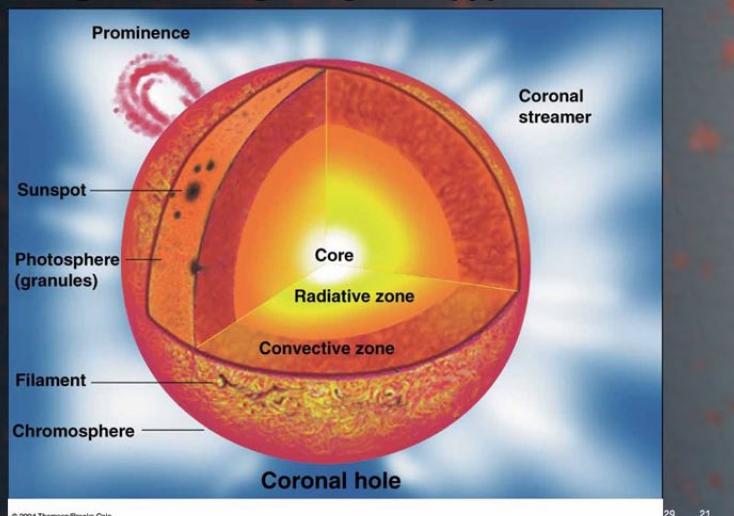


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NICMOS

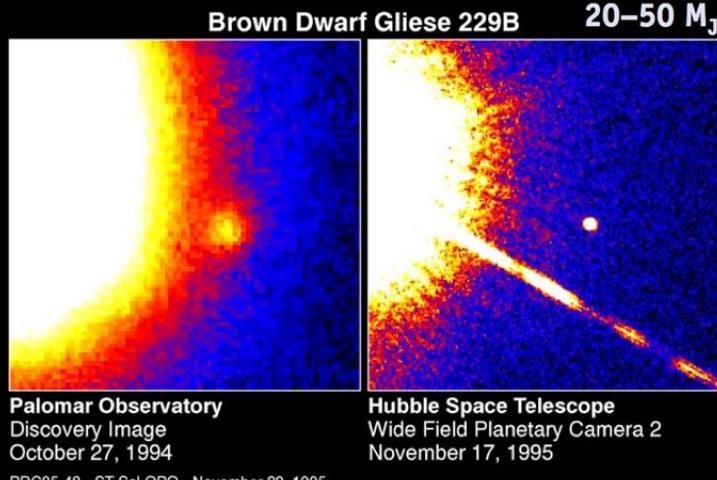
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# A STAR IS BORN...



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...OR NOT.



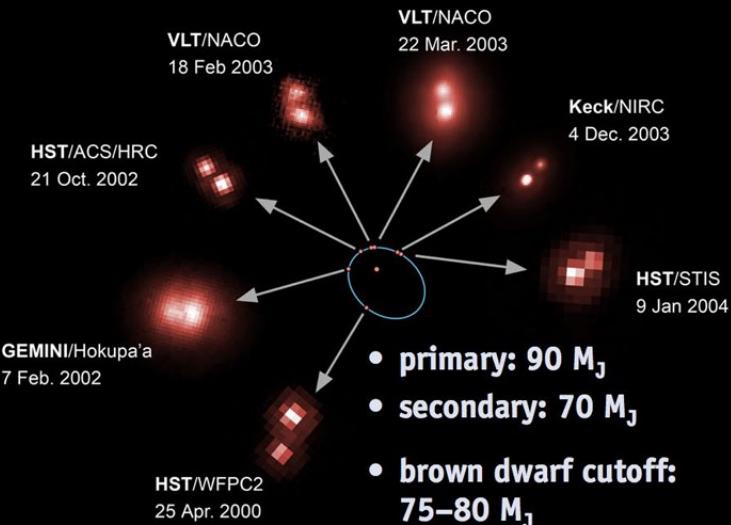
Palomar Observatory  
Discovery Image  
October 27, 1994

Hubble Space Telescope  
Wide Field and Planetary Camera 2  
November 17, 1995

PRC95-48 · ST Scl OPO · November 29, 1995  
T. Nakajima and S. Kulkarni (CalTech), S. Durrance and D. Golimowski (JHU), NASA

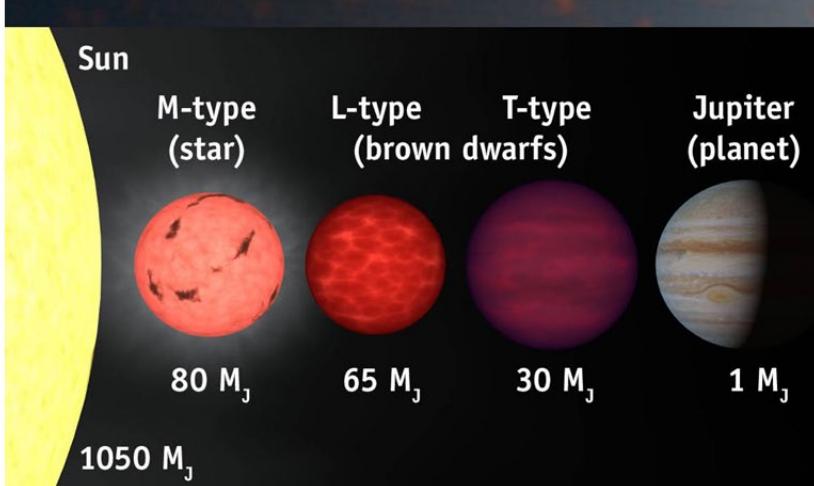
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## L-DWARF BINARY



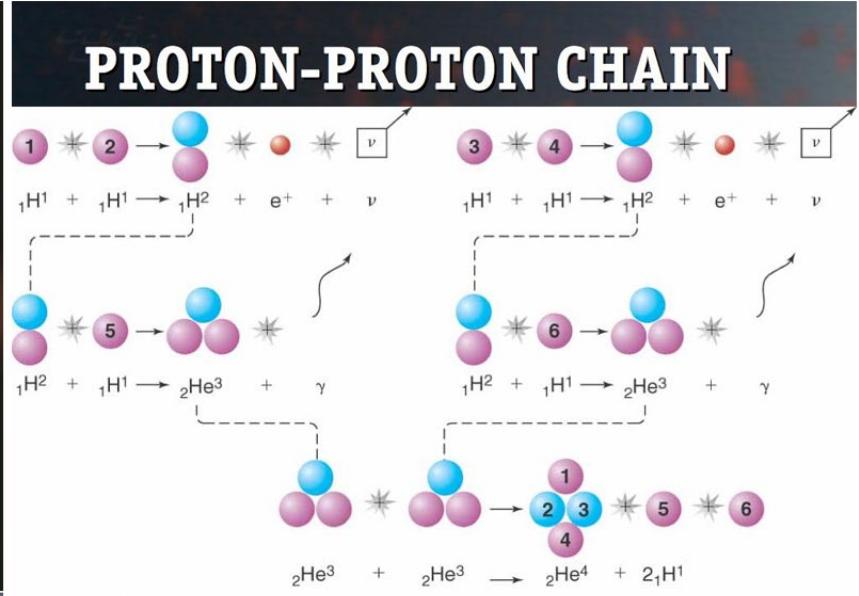
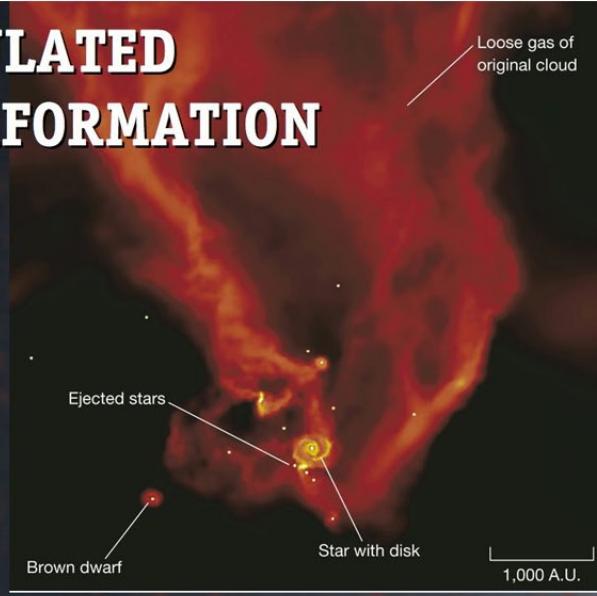
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## BROWN DWARFS



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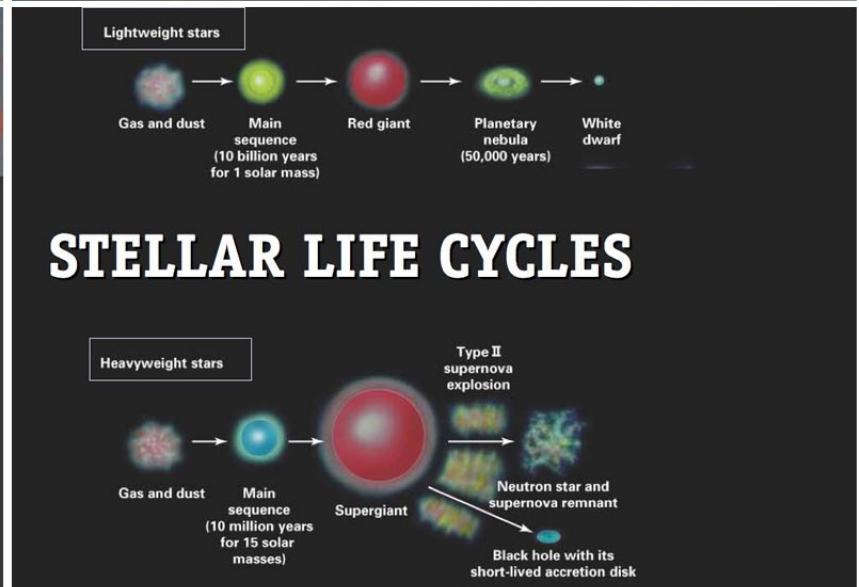
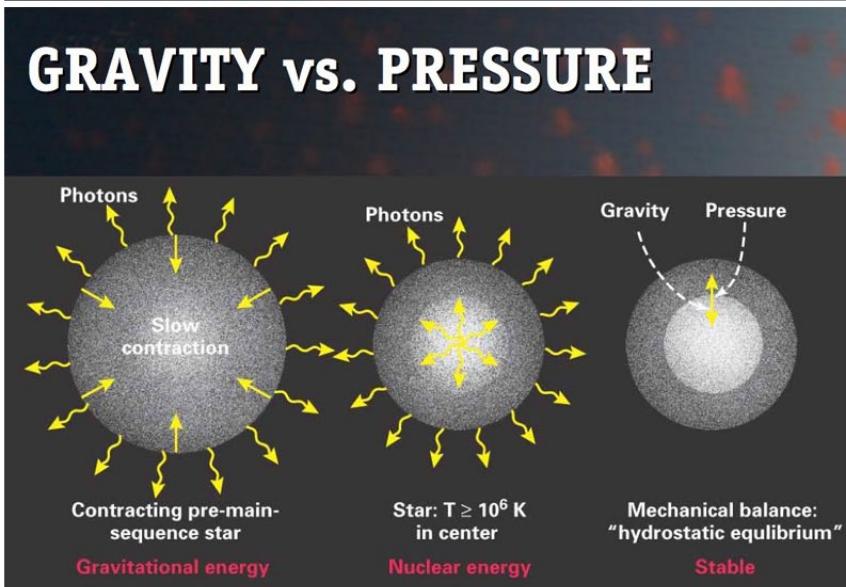
# SIMULATED STARFORMATION



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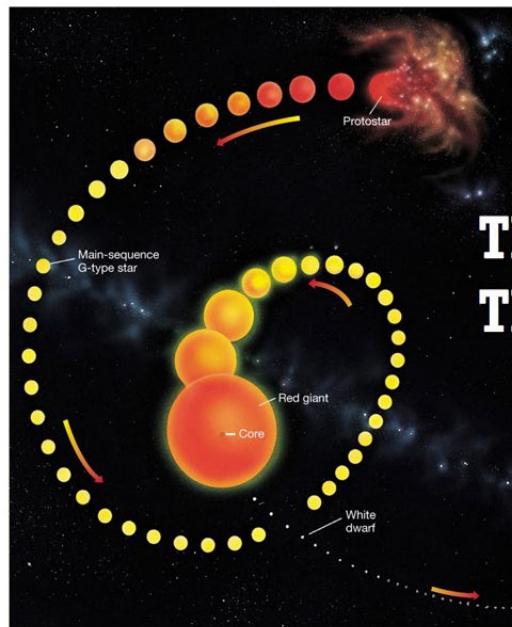
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# GRAVITY vs. PRESSURE



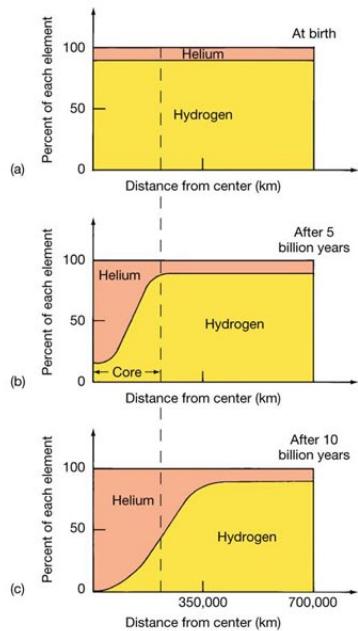
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## THE LIFE OF THE SUN

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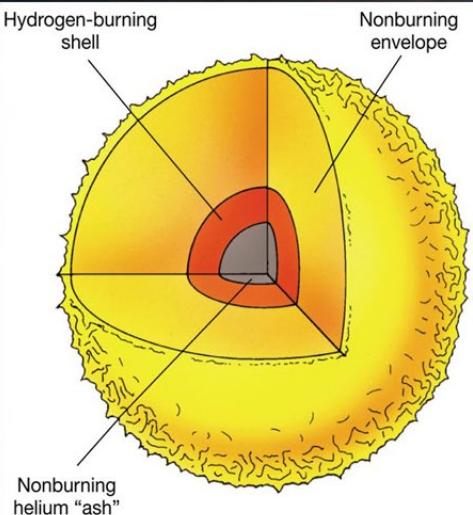


## CORE COMPOSITION

- over billions of years, H gets used up in the core
- He increases over time in the core
- NUCLEOSYNTHESIS** is the conversion from one element to another

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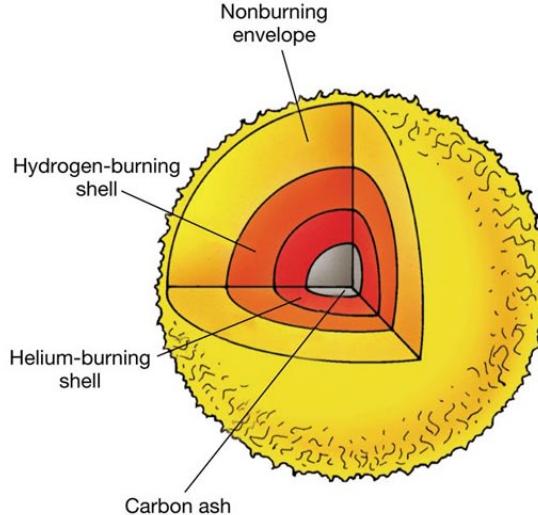
## THE SOLAR INTERIOR



- H fusion continues in a shell around the core when there is no more H in the core
- H-burning is still confined to high-density, high-T regions

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## THE SOLAR INTERIOR



- Concentric shells with different nuclear fuels surround the C-Ne-O core near the end of the Sun's life
- The sun would really be red not yellow

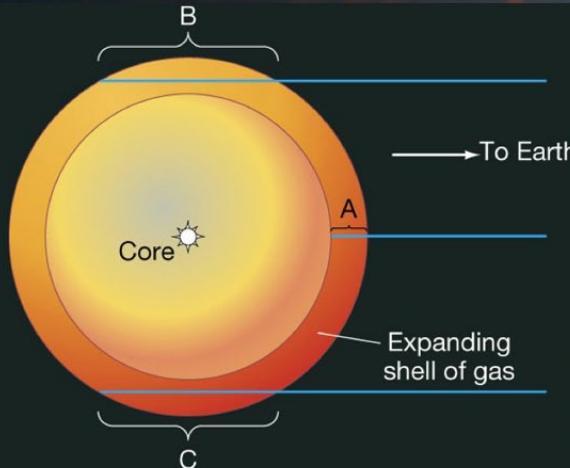
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# PLANETARY NEBULAE

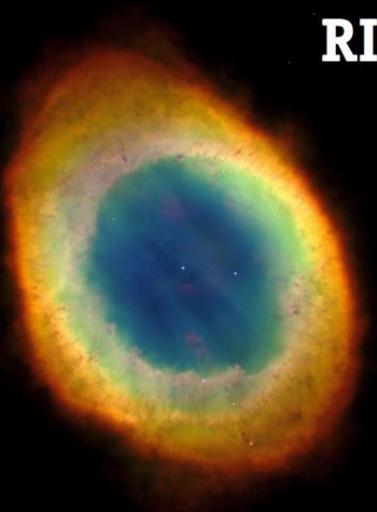


- not really associated with planets
- this is Abell 39
- good spherical symmetry in the expanding shell
- the shell can look like a ring if it is thin

# PLANETARY NEBULAE



# RING NEBULA



- different colors -> different atomic emissions -> different energies

# HELIX NEBULA



- visible light image
- central star clearly visible

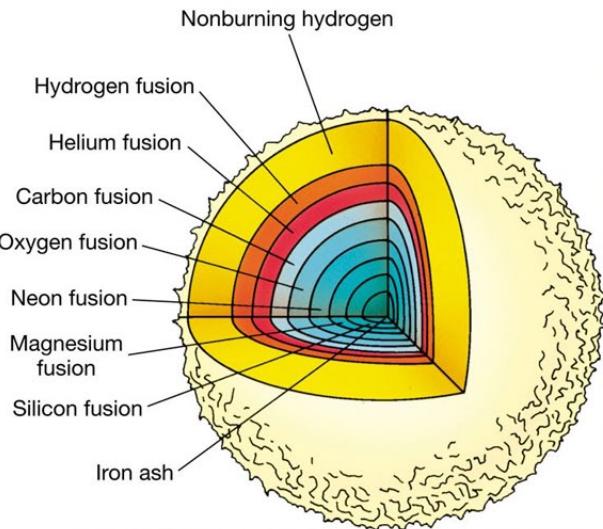
# HELIX NEBULA

nebular  
“knots” are  
~100 AU

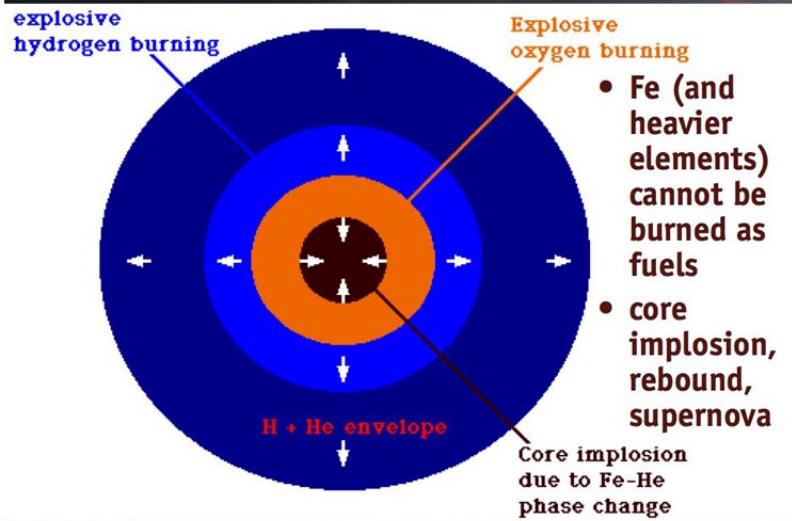


# HEAVY STARS

- higher  $T_s$  in heavy star cores leads to nucleo-synthesis of heavier elements



## HEAVY STAR DEATH

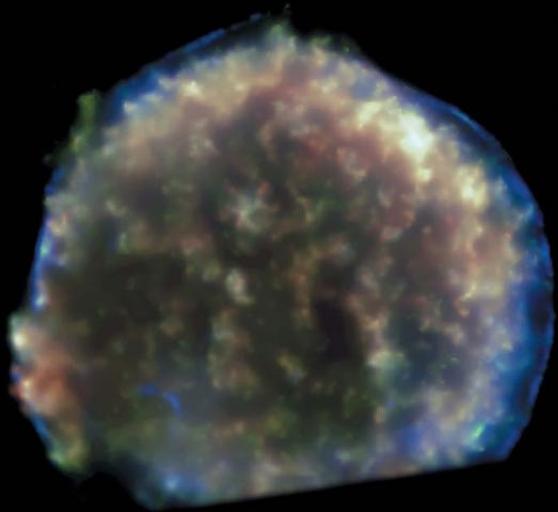


## CRAB NEBULA

- SN observed 1054 AD



- Tycho's SN remnant
- Chandra x-ray image
- SN observed 1604

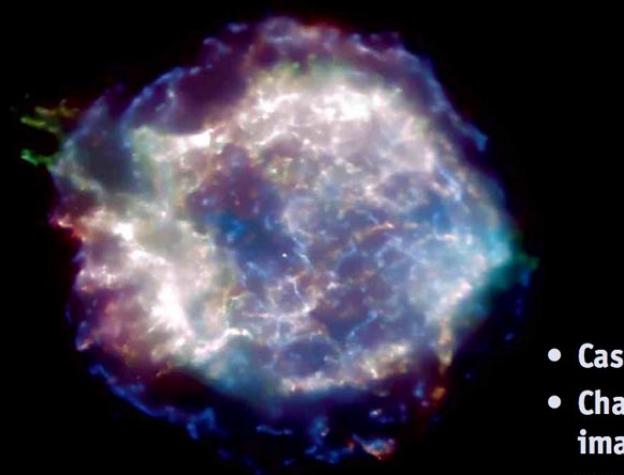


• Vela SN remnant  
• ~9000 BCE

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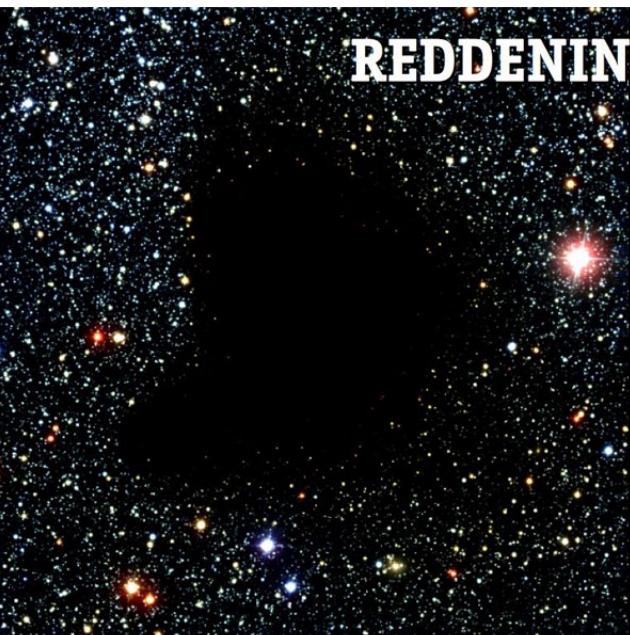
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• Cass A  
• Chandra x-ray image  
• SN in 1680

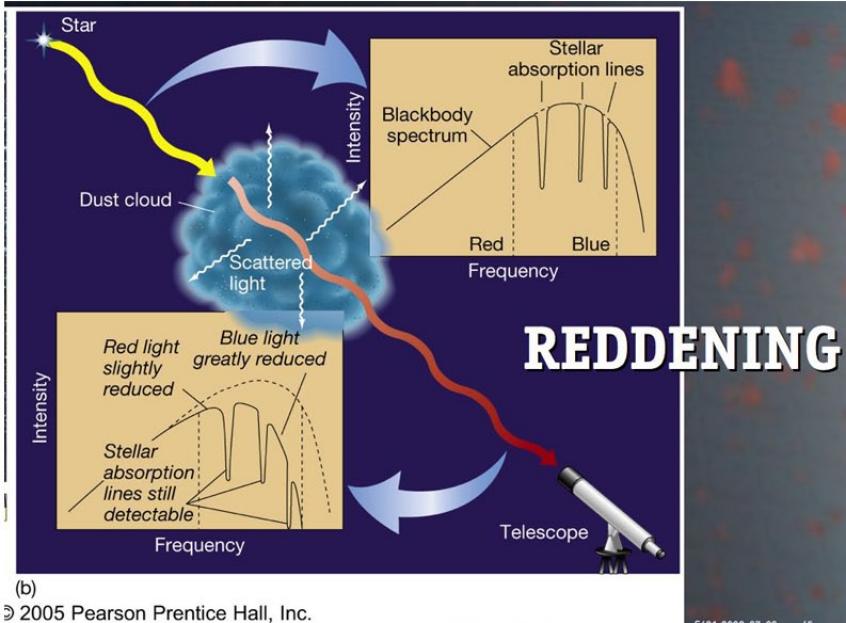
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## REDDENING from dust

- Barnard 68
- 0.2-pc cloud ( $\sim 0.6$  light years across)

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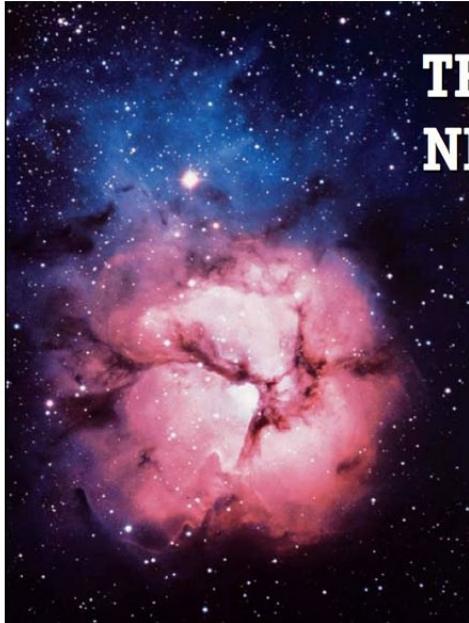
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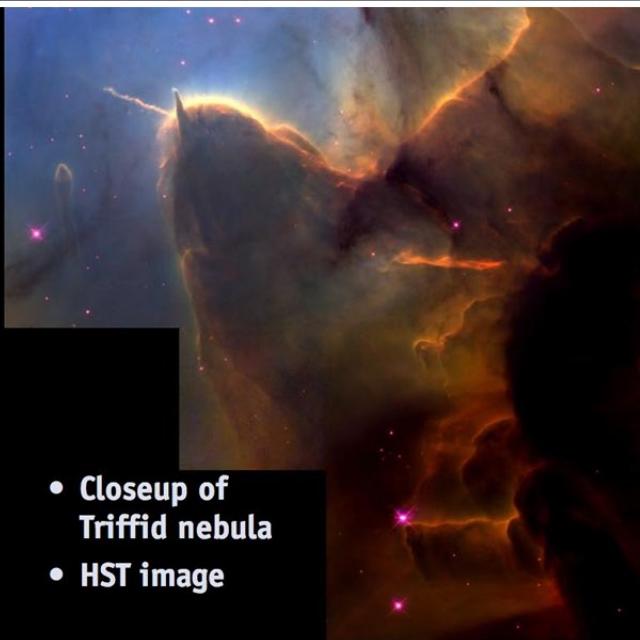
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## TRIFFID NEBULA

- H II region
  - blue: reflected starlight
  - red: H $\alpha$



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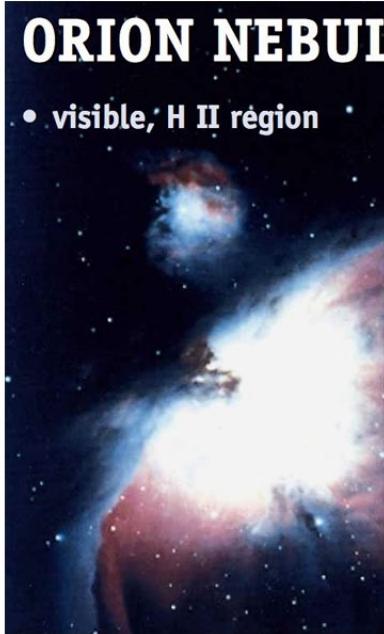


- Closeup of Triffid nebula
- HST image

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## ORION NEBULA

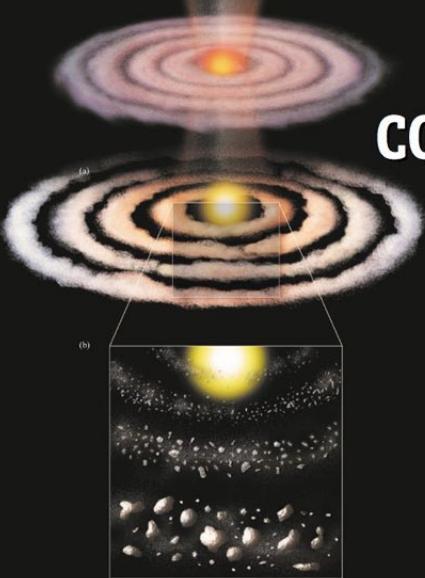
- visible, H II région



- infrared
  - starlight can penetrate the dust

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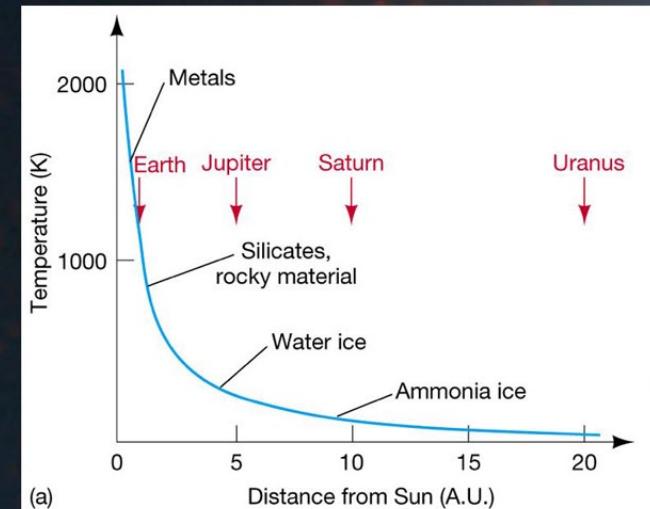
## CONDENSATION

- refractory materials
- volatile materials

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## TEMPERATURE IN THE DISK



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## CHONDRITES and PROTOSOLAR ABUNDANCES

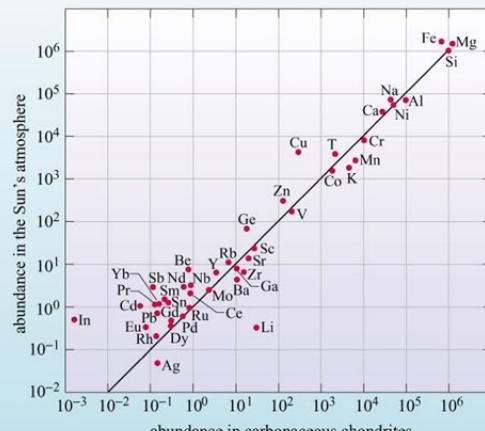


TABLE 2  
Recommended Elemental Abundances of the Proto-Sun (Solar System Abundance)

Element	$A(EI)_0$	$N(EI)_0$	Element	$A(EI)_0$	$N(EI)_0$	Element	$A(EI)_0$	$N(EI)_0$
H .....	$\equiv 12$	$2.431 \times 10^{10}$	Ge .....	$3.70 \pm 0.05$	120.6	Sm .....	$1.02 \pm 0.04$	0.2542
He .....	$10.984 \pm 0.02$	$2.343 \times 10^9$	As .....	$2.40 \pm 0.05$	6.089	Sm* .....	$1.02 \pm 0.04$	0.2554
Li .....	$3.35 \pm 0.06$	5547	Sc .....	$3.43 \pm 0.04$	65.79	Eu .....	$0.60 \pm 0.04$	0.09513
Bc .....	$1.48 \pm 0.08$	0.7374	Br .....	$2.67 \pm 0.09$	11.32	Gd .....	$1.13 \pm 0.02$	0.3321
B .....	$2.85 \pm 0.04$	17.32	Kr .....	$3.36 \pm 0.08$	55.15	Tb .....	$0.38 \pm 0.03$	0.05907
C .....	$8.46 \pm 0.04$	$7.079 \times 10^8$	Rb .....	$2.43 \pm 0.06$	6.572	Dy .....	$1.21 \pm 0.04$	0.3862
N .....	$7.90 \pm 0.11$	$1.950 \times 10^8$	Rb* .....	$2.44 \pm 0.06$	6.694	Ho .....	$0.56 \pm 0.02$	0.08986
O .....	$8.76 \pm 0.05$	$1.413 \times 10^7$	Sr .....	$2.99 \pm 0.04$	23.64	Er .....	$1.02 \pm 0.03$	0.2554
F .....	$4.53 \pm 0.06$	841.1	Sr* .....	$2.99 \pm 0.04$	23.52	Tm .....	$0.18 \pm 0.06$	0.03700
Ne .....	$7.95 \pm 0.10$	$2.148 \times 10^8$	Y .....	$2.28 \pm 0.03$	4.608	Yb .....	$1.01 \pm 0.03$	0.2484
Na .....	$6.37 \pm 0.03$	$5.751 \times 10^8$	Zr .....	$2.67 \pm 0.03$	11.33	Lu .....	$0.16 \pm 0.06$	0.03572
Mg .....	$7.62 \pm 0.02$	$1.020 \times 10^8$	Nb .....	$1.49 \pm 0.03$	0.7554	Lu* .....	$0.17 \pm 0.06$	0.03580
Al .....	$6.54 \pm 0.02$	$8.410 \times 10^8$	Mo .....	$2.03 \pm 0.04$	2.601	Hf .....	$0.84 \pm 0.04$	0.1699
Si .....	$7.61 \pm 0.02$	$\equiv 1.00 \times 10^8$	Ru .....	$1.89 \pm 0.08$	1.900	Hf* .....	$0.84 \pm 0.04$	0.1698
P .....	$5.54 \pm 0.04$	8373	Rh .....	$1.18 \pm 0.03$	0.3708	Ta .....	$-0.06 \pm 0.03$	0.02099
S .....	$7.26 \pm 0.04$	$4.449 \times 10^5$	Pd .....	$1.77 \pm 0.03$	1.435	W .....	$0.72 \pm 0.03$	0.1277
Cl .....	$5.33 \pm 0.06$	5237	Ag .....	$1.30 \pm 0.06$	0.4913	Re .....	$0.33 \pm 0.04$	0.05254
Ar .....	$6.62 \pm 0.08$	$1.025 \times 10^5$	Cd .....	$1.81 \pm 0.03$	1.584	Re* .....	$0.36 \pm 0.04$	0.05509
K .....	$5.18 \pm 0.05$	3692	In .....	$0.87 \pm 0.03$	0.1810	Os .....	$1.44 \pm 0.03$	0.6758
K' .....	$5.18 \pm 0.05$	3697	Sn .....	$2.19 \pm 0.04$	3.733	Os* .....	$1.44 \pm 0.03$	0.6713
Ca .....	$6.41 \pm 0.03$	$6.287 \times 10^4$	Sb .....	$1.14 \pm 0.07$	0.3292	Ir .....	$1.42 \pm 0.03$	0.6448
Sc .....	$3.15 \pm 0.04$	3420	Te .....	$2.30 \pm 0.04$	4.815	Pt .....	$1.75 \pm 0.03$	1.357
Ti .....	$5.00 \pm 0.03$	2422	I .....	$1.61 \pm 0.12$	0.9975	Au .....	$0.91 \pm 0.06$	0.1955
V .....	$4.07 \pm 0.03$	288.4	Xe .....	$2.35 \pm 0.02$	5.391	Hg .....	$1.23 \pm 0.18$	0.4128
Cr .....	$5.72 \pm 0.05$	$1.286 \times 10^4$	Cs .....	$1.18 \pm 0.03$	0.3671	Tl .....	$0.88 \pm 0.04$	0.1845
Mn .....	$5.58 \pm 0.03$	9168	Ba .....	$2.25 \pm 0.03$	4.351	Pb .....	$2.13 \pm 0.04$	3.258
Fe .....	$7.54 \pm 0.03$	$8.380 \times 10^3$	La .....	$1.25 \pm 0.06$	0.4405	Pb* .....	$2.12 \pm 0.04$	3.224
Co .....	$4.98 \pm 0.03$	2323	Ce .....	$1.68 \pm 0.02$	1.169	Bi .....	$0.76 \pm 0.03$	0.1388
Ni .....	$6.29 \pm 0.03$	$4.780 \times 10^4$	Pr .....	$0.85 \pm 0.03$	0.1737	Th .....	$0.16 \pm 0.04$	0.03512
Cu .....	$4.34 \pm 0.06$	527.0	Nd .....	$1.54 \pm 0.03$	0.8355	Th* .....	$0.26 \pm 0.04$	0.04399
Zn .....	$4.70 \pm 0.04$	1226	Nd* .....	$1.54 \pm 0.03$	0.8343	U .....	$-0.42 \pm 0.04$	$9.306 \times 10^{-3}$
Ga .....	$3.17 \pm 0.06$	35.97	U* .....	$+0.01 \pm 0.04$	$24.631 \times 10^{-3}$			

Note.—Values for elements marked with an asterisk are abundances  $4.55 \times 10^8$  yr ago. Mass fractions for proto-Sun:  $X_0 = 0.7110$ ,  $Y_0 = 0.2741$ ,  $Z_0 = 0.0149$ , and  $X_0/Z_0 = 0.0210$ . The astronomical log scale and the cosmochemical abundance scale by number are coupled by  $A(EI)_0 = \log[N(EI)] + 1.614$ .

Substance	Formula	Temperature of condensation <sup>a</sup> (K)
<i>ionic substances</i>		
corundum	Al <sub>2</sub> O <sub>3</sub>	1758
perovskite	CaTiO <sub>3</sub>	1647
spinel	MgAl <sub>2</sub> O <sub>4</sub>	1513
nickel-iron metal	Ni, Fe	1471
pyroxene (diopside)	CaMgSi <sub>2</sub> O <sub>6</sub>	1450
olivine (forsterite)	Mg <sub>2</sub> SiO <sub>4</sub>	1444
alkali feldspars	(Na,K)AlSi <sub>3</sub> O <sub>8</sub>	<1000
troilite	FeS	700
hydrated minerals <sup>b</sup>	(variable)	550–330
<i>molecular substances</i>		
water	H <sub>2</sub> O (as an ice)	180
ammonia	NH <sub>3</sub> , H <sub>2</sub> O (ice)	120
methane	CH <sub>4</sub> , H <sub>2</sub> O (ice)	70
nitrogen	N <sub>2</sub> , H <sub>2</sub> O (ice)	70

## CONDENSATION SEQUENCE

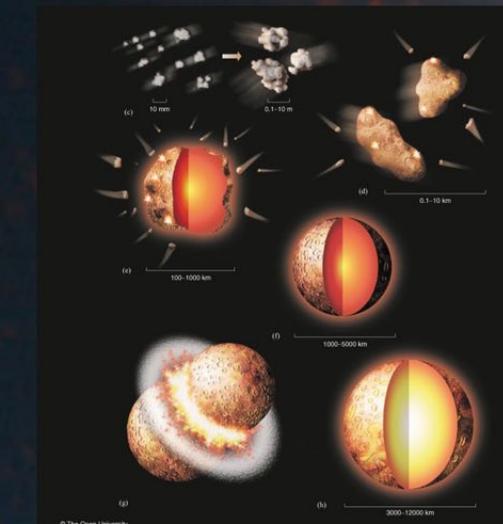
<sup>a</sup>The temperatures of condensation given are those that would occur if the pressure in the nebula had been about  $10^{-3}$  bar ( $10^2$  Pa). At lower pressures, the condensation temperatures would have been reduced slightly.

<sup>b</sup> Hydrated minerals are chiefly silicates with OH or H<sub>2</sub>O in their formulae.

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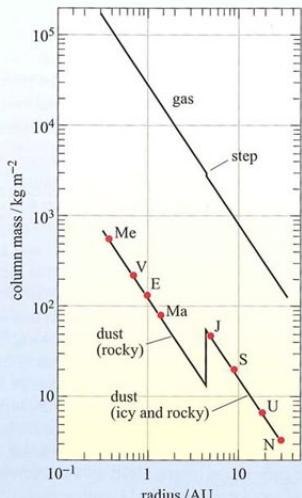
# PLANET FORMATION

- coagulation
- planetesimals
  - gravitational focusing begins
- planetary embryos
- giant impacts and planets



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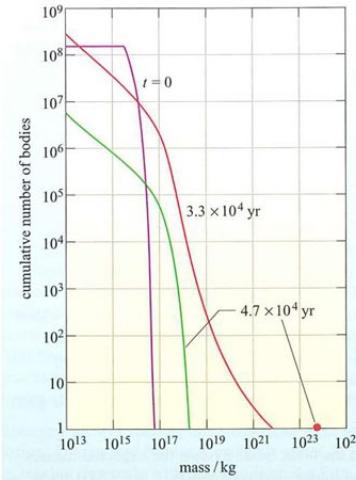
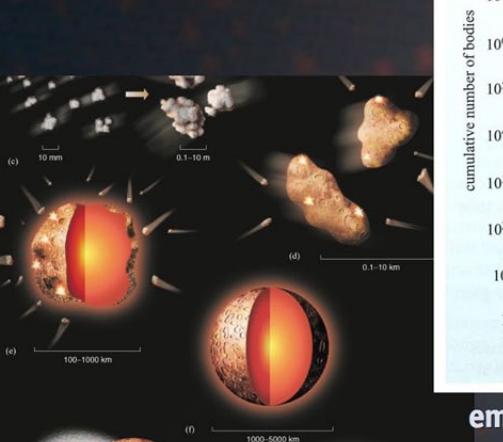
## COAGULATION



solar nebula column density

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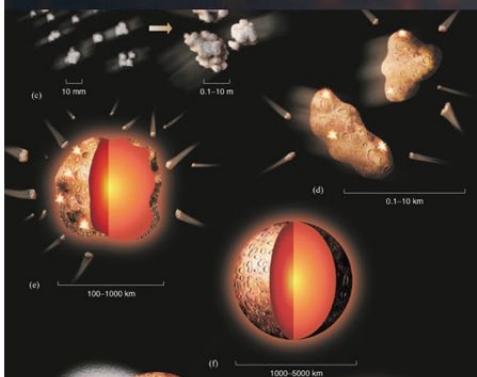
## ACCRETION



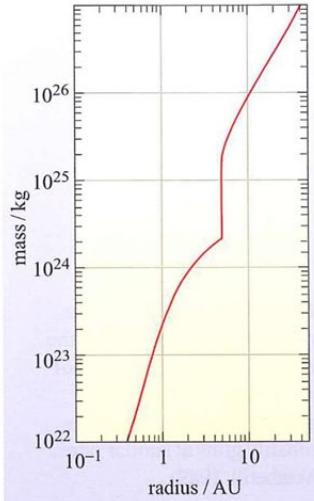
embryo growth

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# ACCRETION



final embryo masses

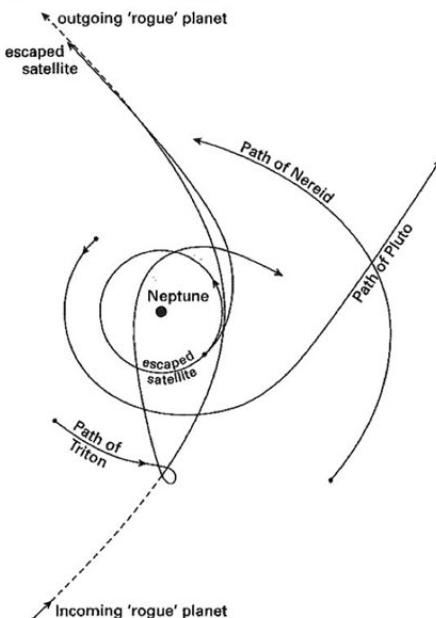


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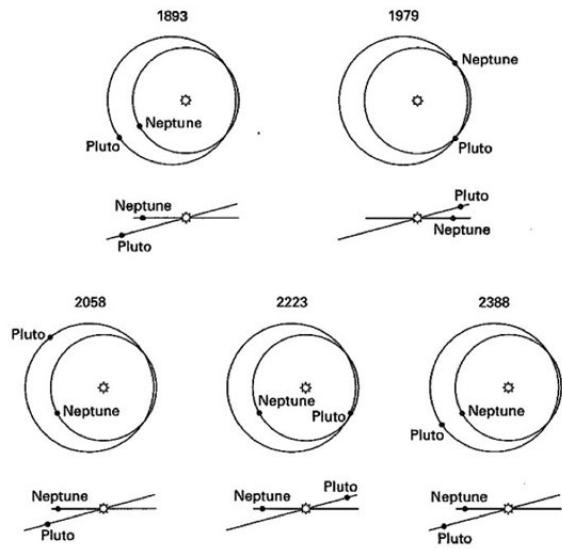
# PLANET BUILDING

- GRAINS -- dust, form by condensation, grow by sticking, coagulation
- PLANETESIMALS -- grow by accretion, gravitational focusing becomes important for large planetesimals
- PLANETARY EMBRYOS or PROTO-PLANETS -- grow by giant impacts, gravitational focusing is very important, can perturb each others' orbits

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9 59

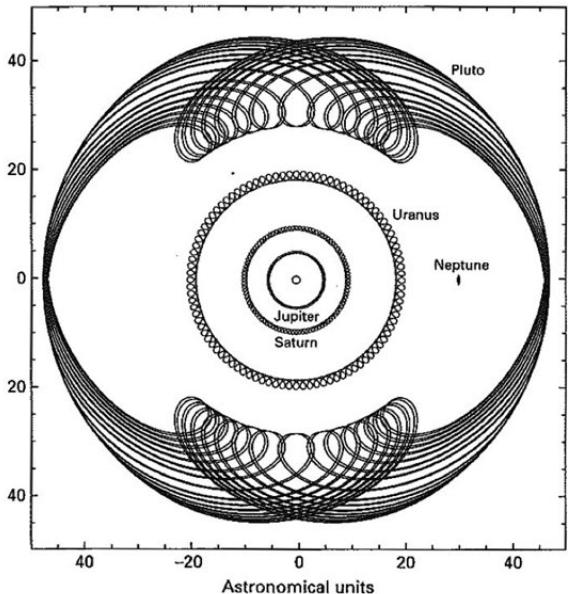


1 Neptune orbit after 1893  
2/3 of a Pluto orbit after 1893

2 Neptune orbits after 1893  
1 1/3 Pluto orbits after 1893

3 Neptune orbits after 1893  
2 Pluto orbits after 1893

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# GIANT IMPACTS

during the planetary embryo accretion stage



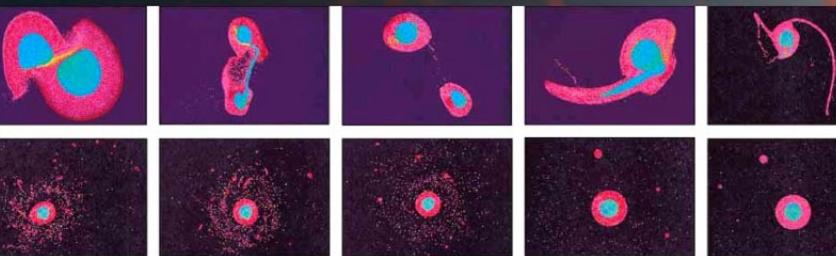
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## IMPACT ON THE EARLY EARTH



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## MOON-FORMING IMPACT



004 Thomson/Brooks Cole

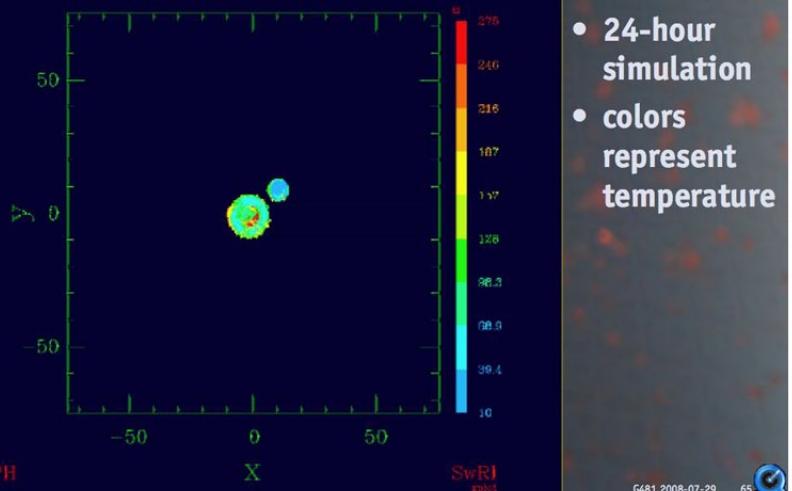
- 6-day simulation
- colors represent density

- iron:  $\sim 8 \text{ g / cm}^3$
- rock:  $\sim 3 \text{ g / cm}^3$
- ice:  $1 \text{ g / cm}^3$
- Earth average:  $5.5 \text{ g / cm}^3$
- Moon average:  $3.3 \text{ g / cm}^3$

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# MOON-FORMING IMPACT

Run 24n



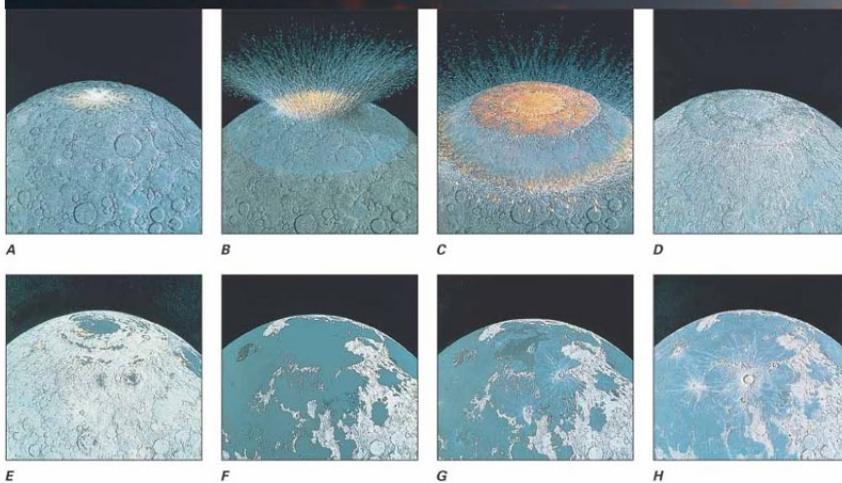
# LUNAR METEORITES



## COMPOSITION:EARTH vs MOON

	CI chondrite (primitive meteorite)	Earth (crust + mantle)	Moon (crust + mantle)	Ratio of trace element abundance Moon/Earth
<b>Volatile<sup>a</sup> elements</b>				
K (ppm)	545	180	83	0.46
Rb (ppm)	2.32	0.55	0.28	0.51
Cs (ppb)	279	18	12	0.67
<b>Moderately volatile</b>				
Mn (ppm)	1500	1000	1200	1.20
<b>Refractory elements</b>				
Cr (ppm)	3975	3000	4200	1.40
Th (ppb)	30	80	112	1.40
Eu (ppb)	87	131	210	1.60
La (ppb)	367	551	900	1.63
Sr (ppm)	7.26	17.8	30	1.69
U (ppb)	12	18	33	1.83
<b>Siderophile<sup>b</sup> elements</b>				
Ni (ppm)	16500	2000	400	0.200
Mo (ppb)	1380	59	1.4	0.024
Ir (ppb)	710	3	0.01	0.003
Ge (ppb)	48000	1200	3.5	0.003

## MARE IMBRIUM



# ORIGIN OF TERRESTRIAL PLANET ATMOSPHERES

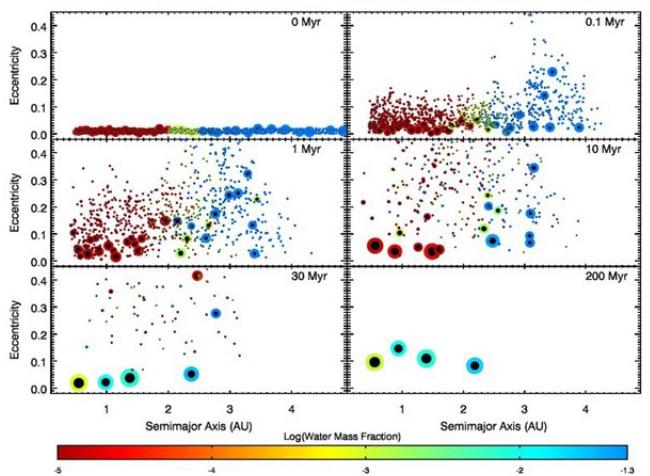
## PRIMARY ATMOSPHERE

- composed of whatever gases available at time of formation
  - hydrogen
  - helium
  - methane ( $\text{CH}_4$ )
  - ammonia ( $\text{NH}_3$ )
  - water ( $\text{H}_2\text{O}$ )
- light gases (H & He) would have rapidly escaped

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## PLANETARY EMBRYO ACCRETION

Raymond et al. 2006



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# ORIGIN OF TERRESTRIAL PLANET ATMOSPHERES

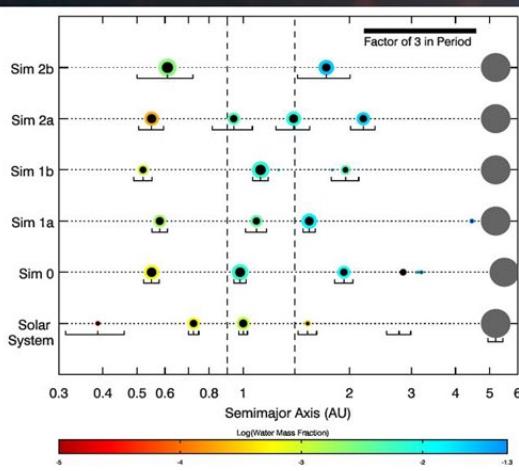
## SECONDARY ATMOSPHERE

- produced by outgassing
  - gases released from melts in the interior
  - volcanically introduced
  - water ( $\text{H}_2\text{O}$ )
  - sulfur dioxide ( $\text{SO}_2$ )
  - carbon dioxide ( $\text{CO}_2$ )
  - nitrogen compounds
- also delivered by impacts of asteroids and comets
  - mainly water
  - impacts also REMOVE atmosphere
- interactions with surface

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## PLANETARY EMBRYO ACCRETION

Raymond et al. 2006



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