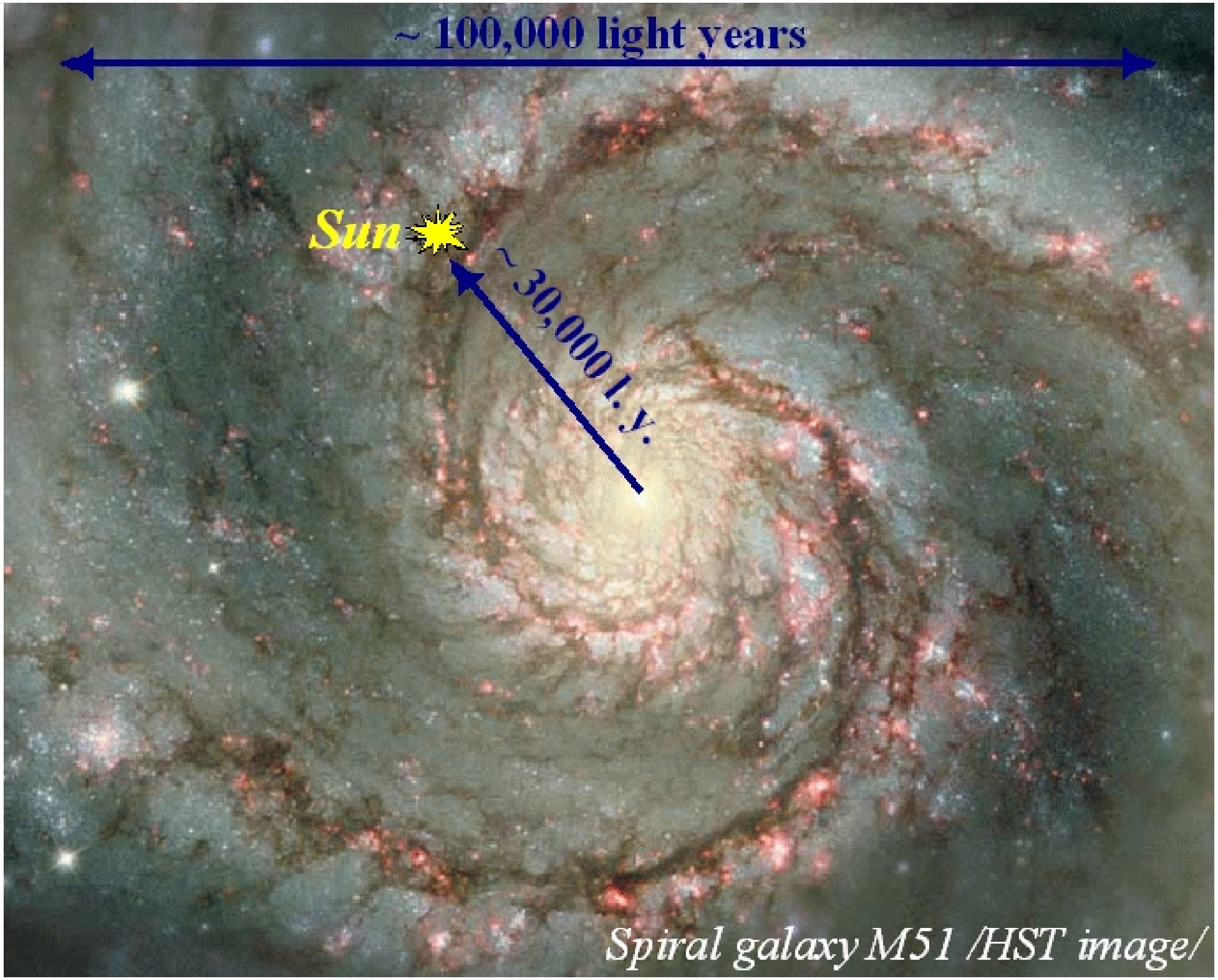
Origin and evolution of planetary atmospheres

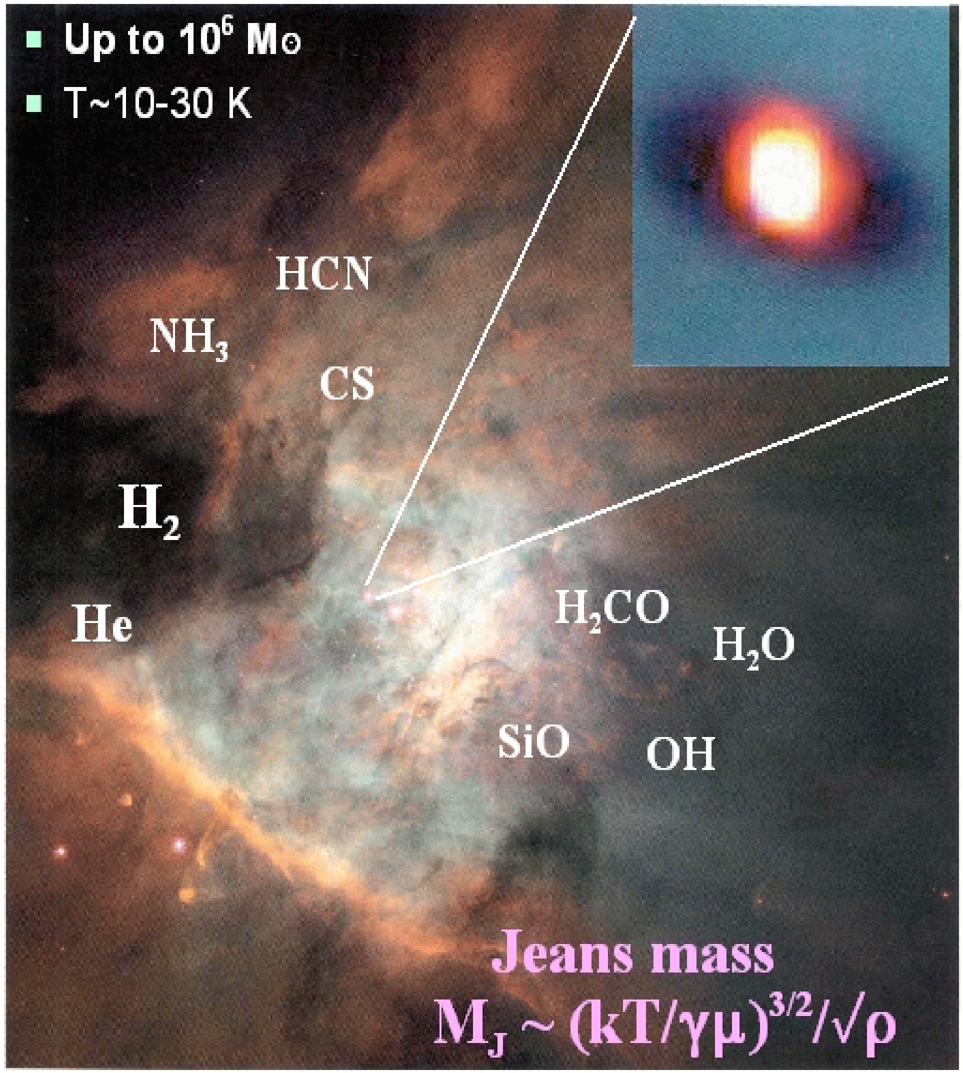
Sun in the Galaxy



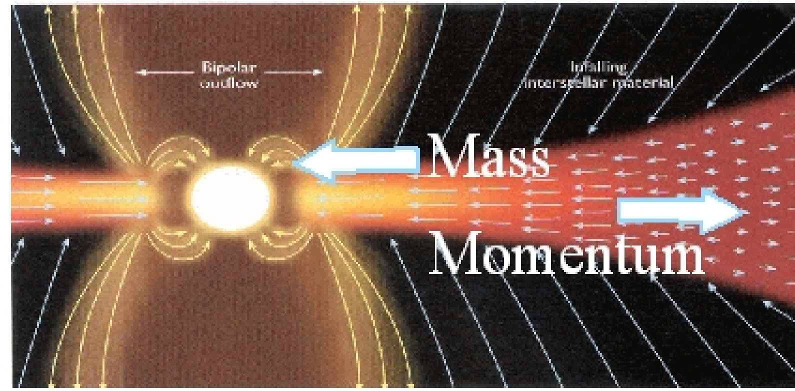
- $N \sim 10^{11}$ stars
- $R_{Sun} \sim 30{,}000$ l.y.
- $\rho \sim 1$ star/300 (l.y.)^3
- $V_{Sun} \sim 250$ km/s
- $T_{Sun} \sim 250$ Myears

Origin of the solar system

Orion nebula



Protoplanetary disc

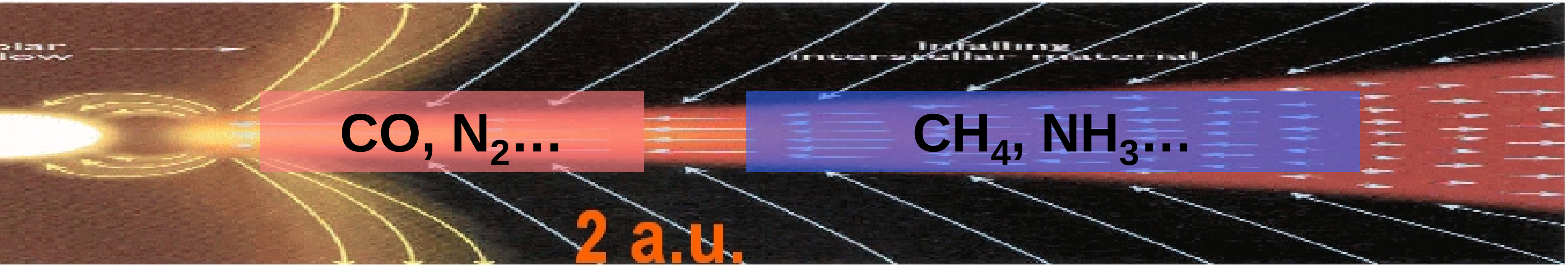


- Gravitational collapse of a molecular cloud ($N \sim 10^4$, T~ 30K)
- Infall stage (10^5 - 10^6 years)
- Formation of protoplanetary disc
- Momentum re-distribution
  - Magnetic field
  - Gravitational torques
  - Turbulent viscosity
- Fragmentation
- Clearing stage (T-Tauri) 10^6 - 10^7 years after protostar formation
- Observations of *proplyds* - disc like structures (~100 a.u.) Around the young stars

Here comes the Sun...

- $R_\odot \sim 7 \cdot 10^5$ km = 109 $R_\oplus$
- $M_\odot \sim 2 \cdot 10^{33}$ g
- $\rho_\odot \sim 1.4$ g/cm^3
- Composition
  - H_2 = 76.4%
  - He = 21.8%
  - Heavy elements < 2%
- Spectral class G2
- $T_{ef} \sim 5800$ K
- Age ~ $5 \cdot 10^9$ years

Formation of planets



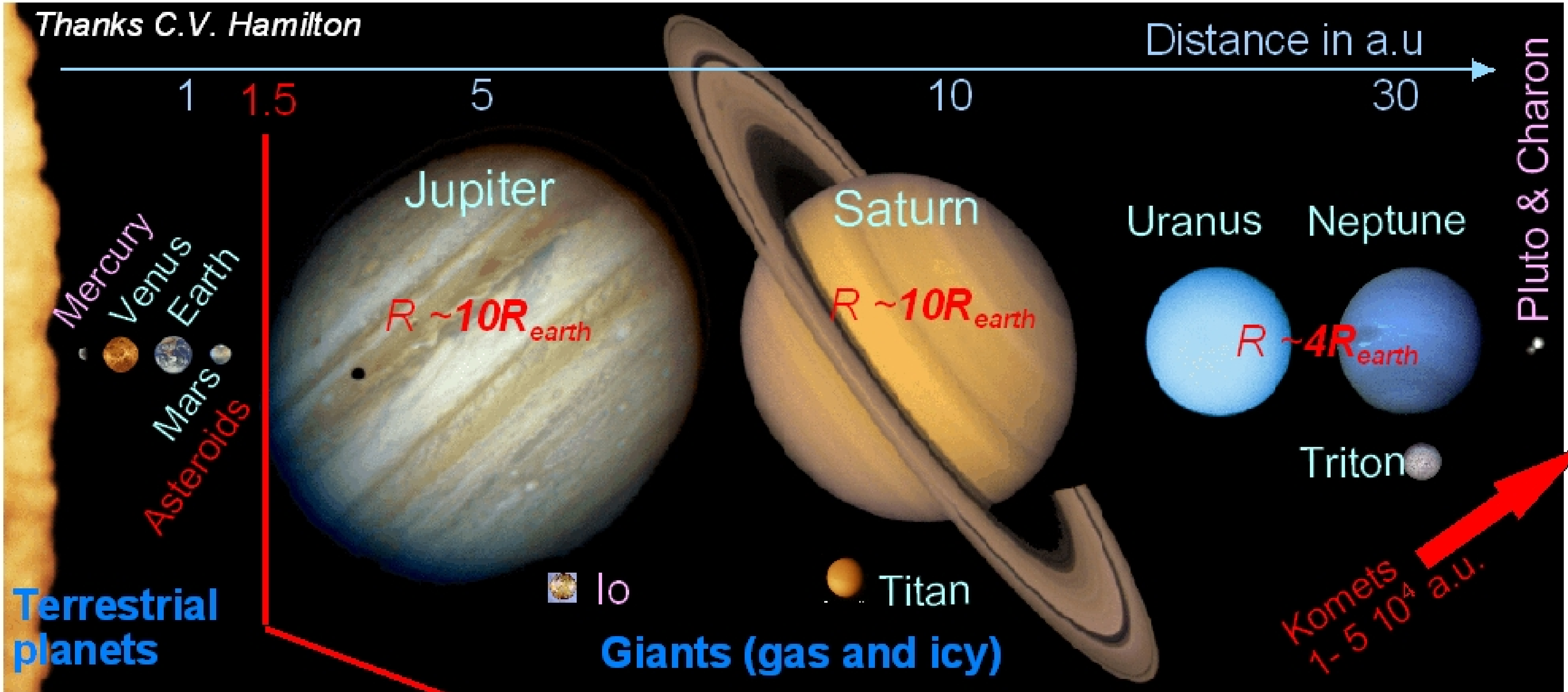
Inner zone

- T~ 500-1000 K
- Silicate and iron compounds
- Chondrules ⇒Fast cooling processes
- Growth to 1 km size planetesimals
  - Gravitational instabity in quiet disc
  - Or two-body colisions in turbulent disc
- From planetesimals to protoplanets
  - Collisions between planetesimals
  - Runaway growth of embrios ($v << v_{esc}$)
  - Time scale ~10^7 - 10^8 years
- Formation of planets
  - Differentiation of interiors
  - Formation of proto-atmospheres (blanketing effect)

Outer zone

- T~ 100K
- H_2 , He and ices H_2O, CO_2, NH_3….
- Significant amount of heavy elements as compared to solar
- Fast accretion of gas (t~10 My)
- Effective accretion of heavy elements
- **Scenario 1: Gravitational collapse**
  - Disagreement with the data on compositio and structure
- **Scenario 2: Accretion + gas accumulatio**
  - Formation of solid core (**$0.1M_{earth}$**, 1My)
  - Gas runaway accretion (**$10M_{earth}$**, 10My)
  - Contraction (~0.01-0.1 My)

Family of the Sun



- $M \sim M_{earth}$
- $\rho \sim 5$ g/cm^3
- Solid bodies, heavy elements
- T > 1 day
- Interior flux << Solar flux

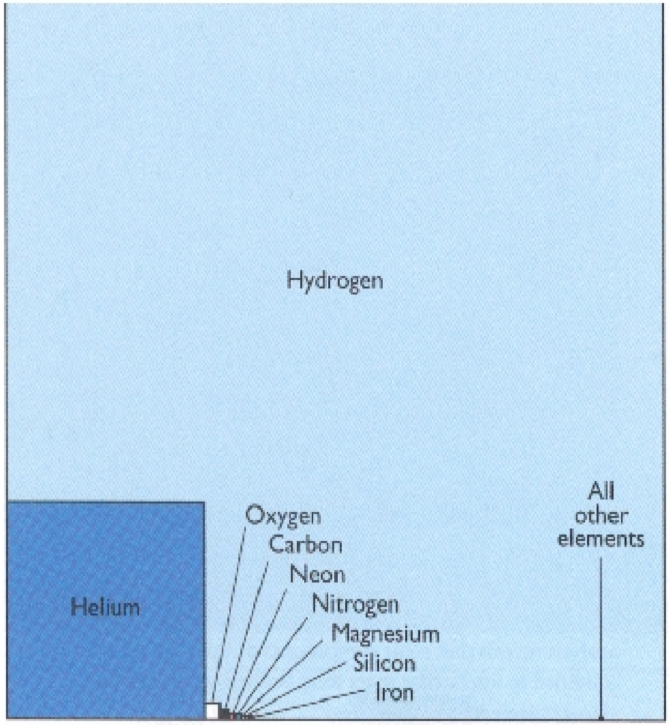
Atmospheres: CO_2, N_2, O_2, H_2O, SO_2

- $M > 20M_{earth}$
- $\rho \sim 1.5$ g/cm^3
- Gas balls with heavy core
- Solar composition (H, He) and H_2O, NH_3, CH_4 ices
- T ~ 8 hours
- Interior flux ~ Solar flux

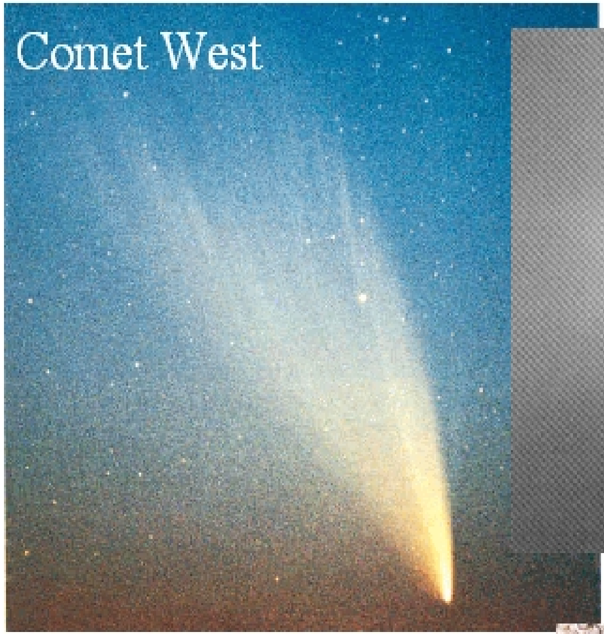
Atmospheres: H_2, He, CH_4, H_2O, NH_3, H_2S

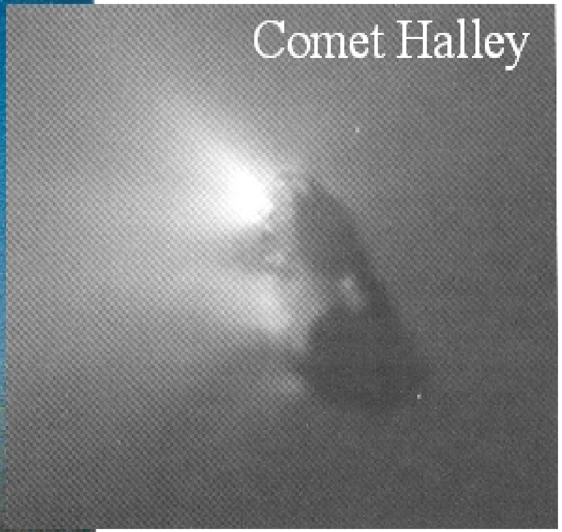
Composition of the nebula

Element abundance

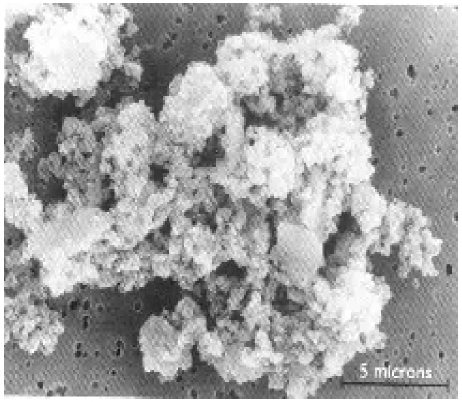


Samples of primitive material

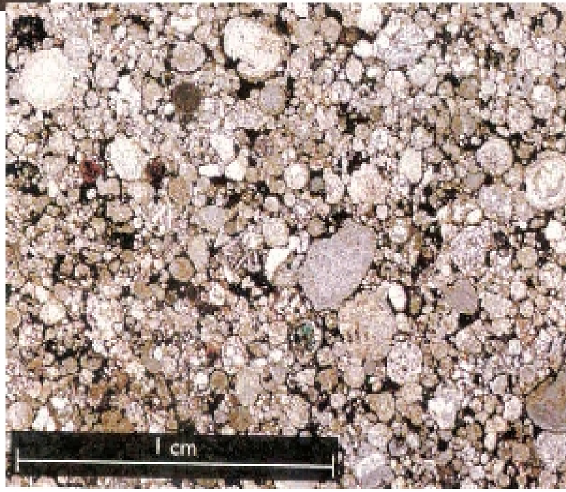




Cometary particles



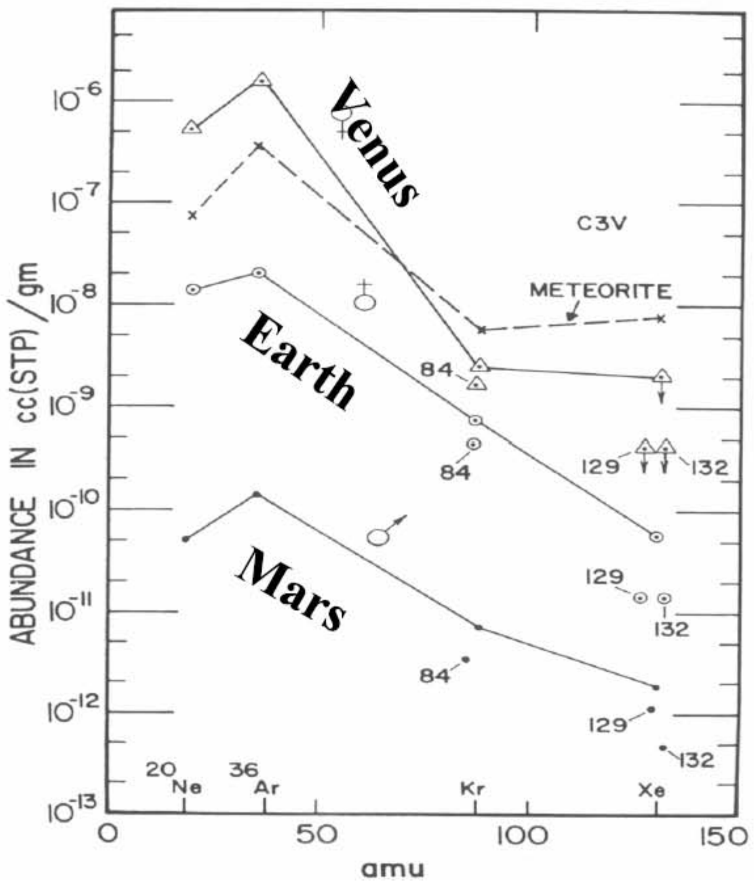
Meteorites



Age ~4.5 By

Records of atmospheric evolution

Noble gases on terrestrial planets

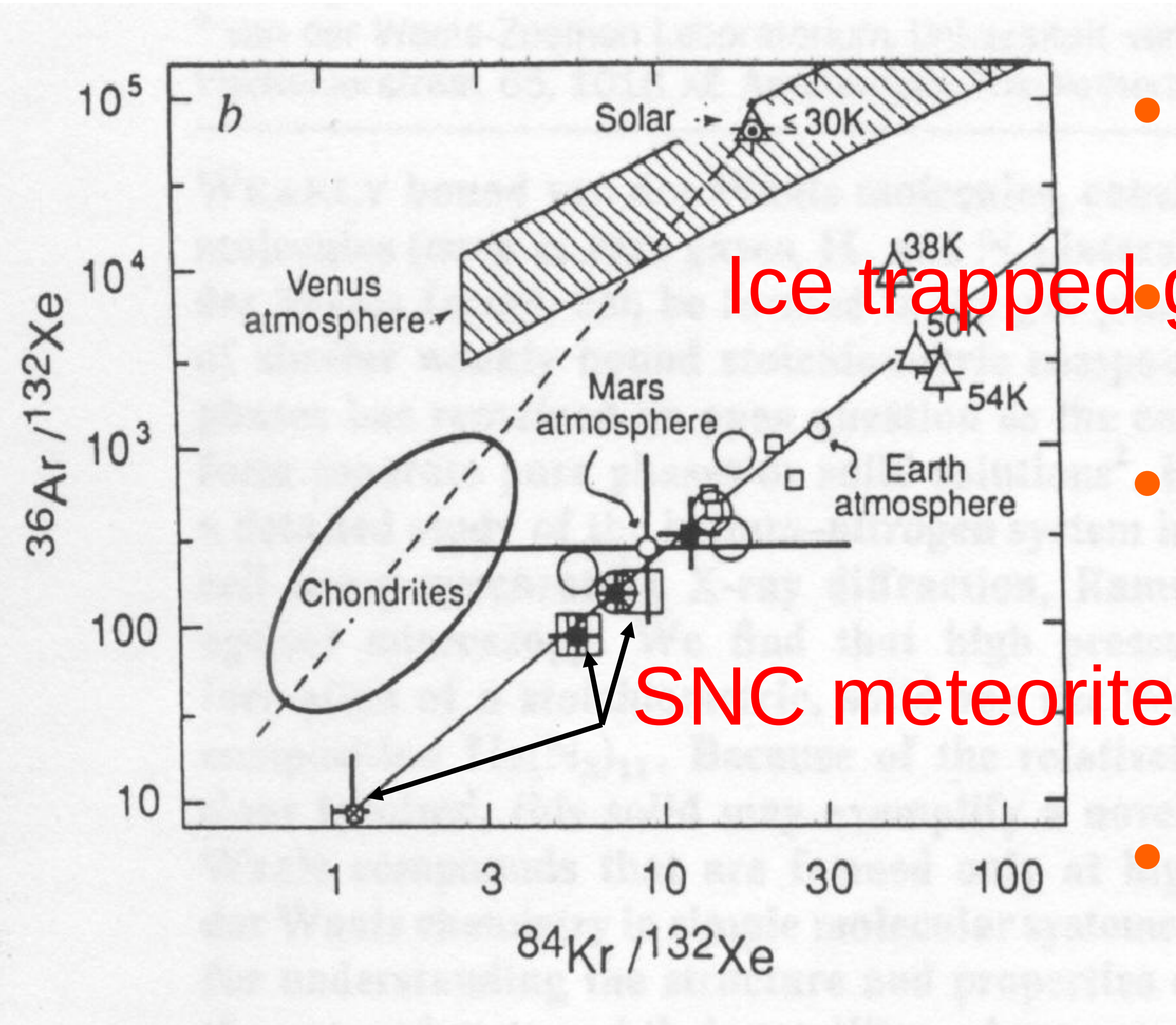


- Terrestrial atmospheres were degassed from planetesimals, not accreted from nebula
- Gases (except Ne) were trapped in the planetesimals at ~30K
- Venus atmosphere is more primordial
- Mars and Earth has possibly survived severe impact erosion
- Possibly two reservoirs - planetesimals and comets - fed Mars and Earth
- $\mathbf{(D/H)_V}$ ~150 $\mathbf{(D/H)_E}$; $\mathbf{(D/H)_M}$ **~ 6** $\mathbf{(D/H)_E}$
  $\Rightarrow$ much greater amonts of water existed on Venus and Mars

Accumulation of planetary atmospheres

- Outgassing during accretion phase
  - $M \sim 0.1\ M_{earth}$
  - $T \sim 1600$ K
  - Melting of the solid body, differentiation, and outgassing
- Volcanic eruptions
- Cometary supply

Two reservoirs of atmospheric material



- Earth and Mars received material from two reservoirs: planetesimals and comets
- ~100 km object is enough to produce observed noble gas pattern
- Ne abundance
  - *Ne is not trapped in the ice and is expected to be primordial*
  - *Hydrodynamic escape on Earth a Mars can explain depletion of Ne*
  - *On Venus - isotope escape differentiation*
- Venus is closer to solar composition

Erosion of planetary atmospheres

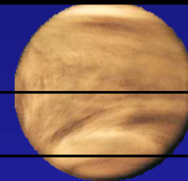
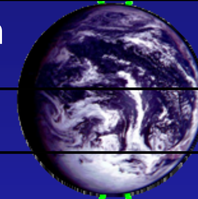
- **Thermal or Jeans escape**
  - Exobase: free path~scale height
  - Simple estimate: $V_{th} > V_{esc}$
  - Maxwellian velocity distribution
  - Escape parameter: $\lambda=(V_{esc}/V_{th})^2$
  - Jeans flux: $\Phi \sim NV_{th}(1+\lambda)\exp(-\lambda) \sim$ $\sim 10^7$ cm^{-2} s^{-1} H atoms from Earth
  - Isotopic fractionation
- **Non-thermal escape**
  - Dissociation and recombination
  - Charge exchange
  - Sputtering
  - Solar wind sweeping
-
- **Hydrodynamic escape (blow off)**
  - Planets during accretion period
- **Impact erosion (d>H)**
  - $M_e/M \sim d^2$

Main factors and processes in evolution of terrestrial planetary atmospheres

- **Earth**
  - removal of CO_2 by silicate weathering (Urey reaction)

  $CO_2 + H_2O + CaSiO_3 \rightarrow$ carbonates ($CaCO_3$)
  - CO_2 recycling by plate tectonics
  - self-regulation of CO2 abundance by weathering and outgassing
  - photosynthesis of O_2
  - antropogenic production of CO_2
- **Venus**
  - runaway greenhouse $\rightarrow$ water escaped to space
  - no liquid water, no plate tectonics $\rightarrow$ CO_2 stays in the atmosphere
  - global resurfacing ~700 MiY ago $\rightarrow$ sulfur-bearing gases
- **Mars**
  - possible impact erosion
  - small size of the planet
  - obliquity changes
  - warmer and wetter climate before ~3.8 BiY $\rightarrow$ CO_2 loss

Why Earth, Mars, Venus so different?

Property	Venus 	Earth 	Mars 
Mass [10^{12}Gt]	4.9	6.0	0.64
Radius [km]	6049	6371	3390
SolarDistance [AU]	0.72	1.0	1.52
SolarConstant [W/m^2]	2613	1367	589
Atmosphere Mass[10^6Gt]	500	5.1	0.31
N_2 [%]	<2	78	<3
O_2 [%]	$<10^{-4}$	21	<0.25
CO_2 [%]	98	0.035	>96
H_2O[%]	<0.3	<4	<0.001
D/H ratio [10^{-4}]	240	1.5	9
EscapeVelocity** [km/s]	10.3	10.8	4.8
EscapeEnergy [eV]	H:0.54 O:8.64	H:0.61 O:9.69	H:0.12 O:1.91
ExobaseTemp* [K]	275	1000	300
ExobaseAltitude* [km]	200	500	250
IonosphereAltitude*** [km]	120	300	150
ThermalEscape [t/a]	0.0013	2800	7800

*Upper limit of collisional domain **at exobase ***electron peak density