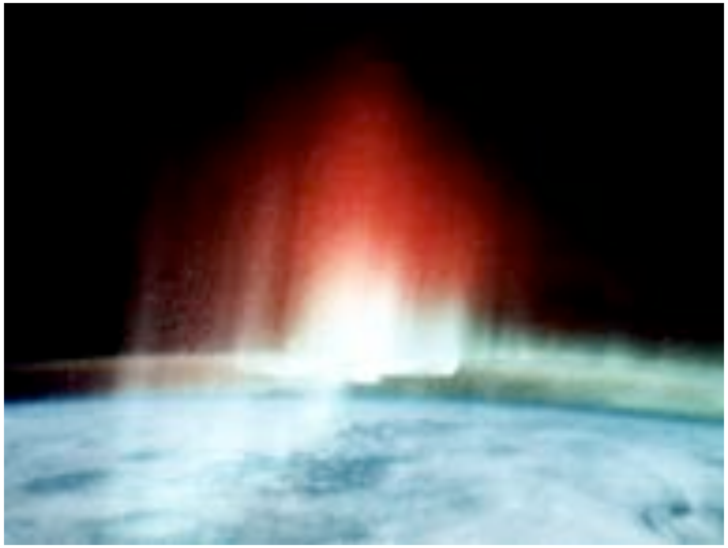
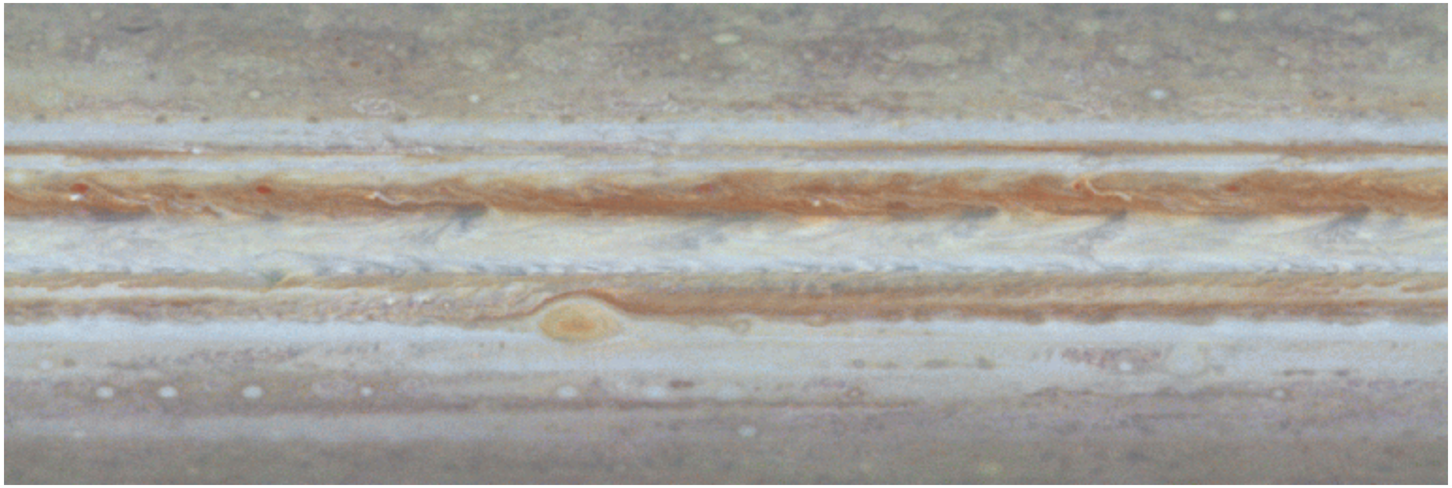
# Planetary Atmospheres

Structure
Composition
Clouds
Photochemistry
Meteorology
Atmospheric Escape

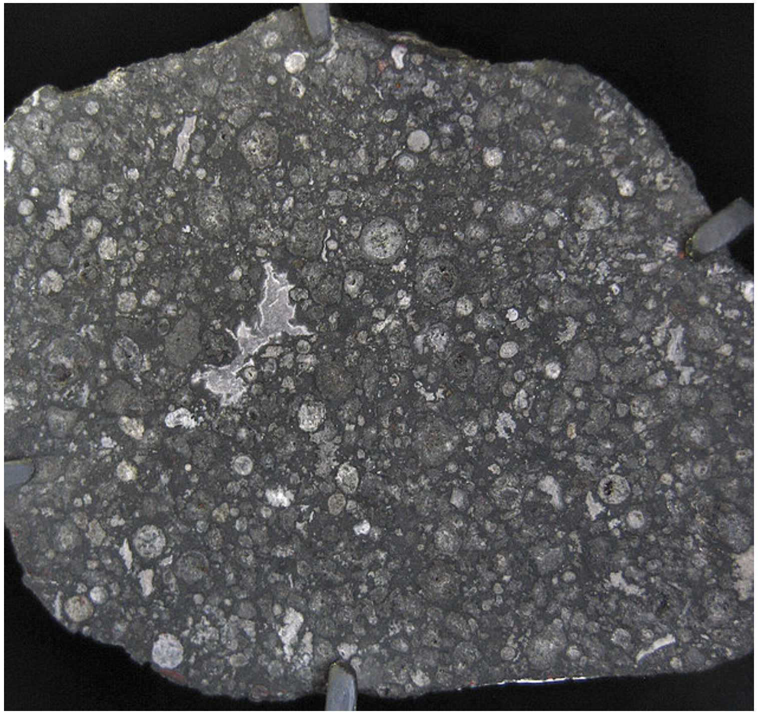


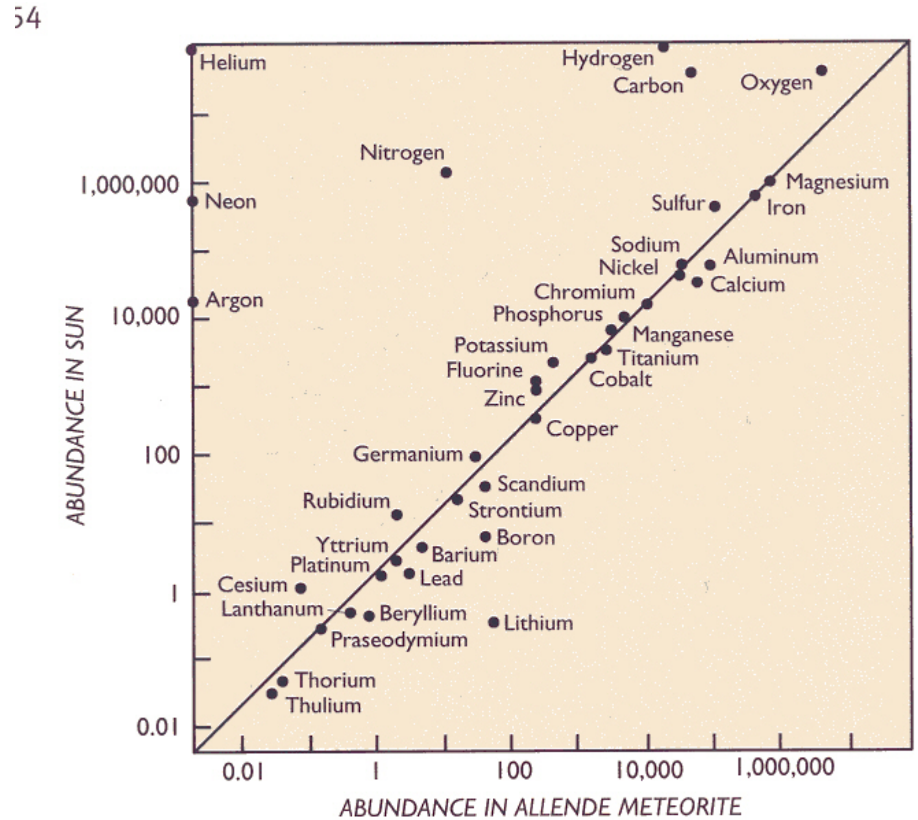


# Where do planetary atmospheres come from?

- Three primary sources
  - Primordial (solar nebula)
  - Outgassing (trapped gases)
  - Later delivery (comets/asteroids)
- How can we distinguish these?
  - Solar nebula composition well known (see next slide)
  - Noble gases are useful because they don't react
  - Isotopic ratios are useful because they may indicate gas loss or source regions (e.g. D/H)
  - $^{40}Ar$ ($^{40}K$ decay product) is a tracer of outgassing

# Carbonaceous chondrites






Compositions from Allende meteorite ⇒

Ref.: J. K. Beatty et al., *The New Solar System*, Ch. 26

Carbonaceous chondrites are considered to be the most similar in composition to the solar nebula

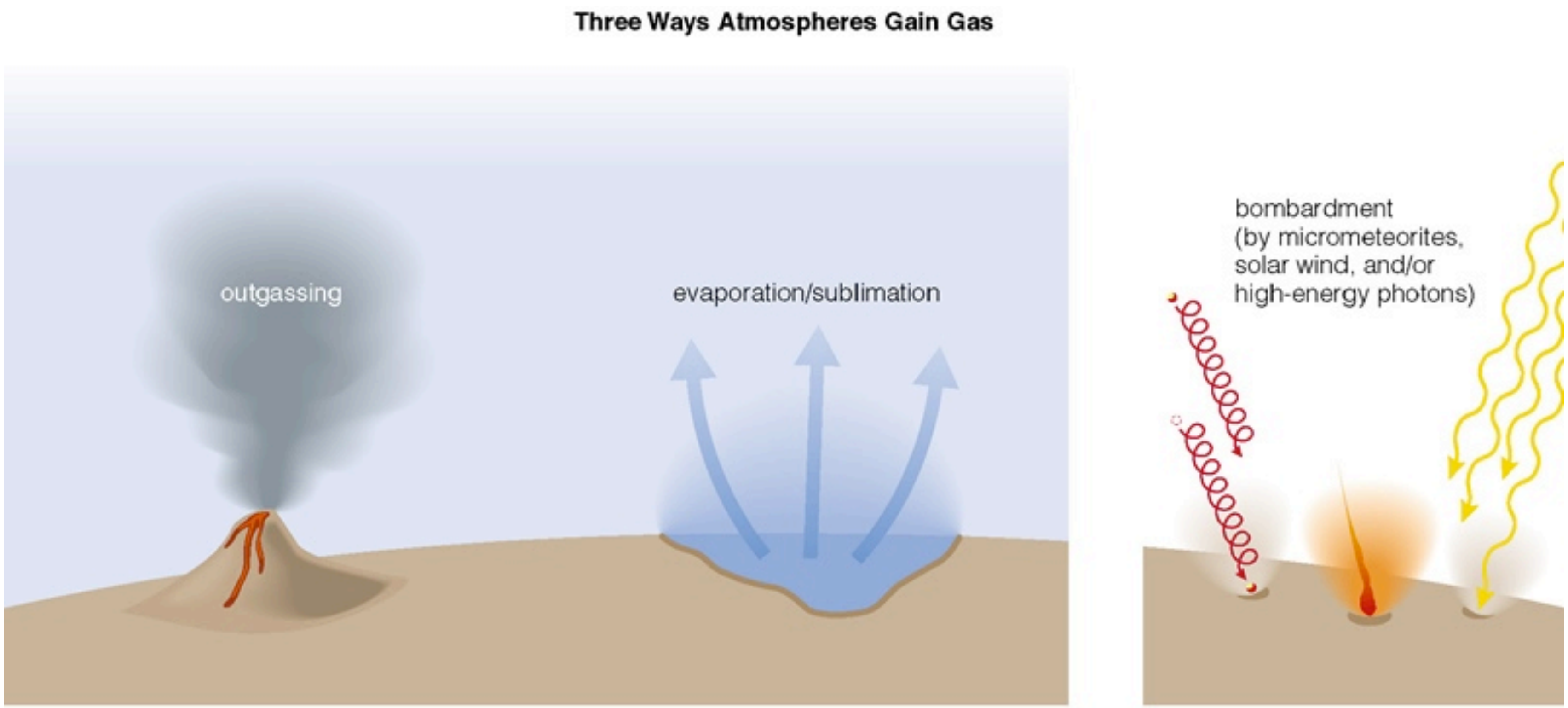
# Not primordial!

- Terrestrial planet atmospheres are not primordial
- Why not?
  - Gas loss (due to impacts, rock reactions or Jeans escape)
  - Chemical processing (e.g. photolysis, rock reactions)
  - Later additions (e.g. comets, asteroids)
- Giant planet atmospheres are *close* to primordial:

| | Solar | Jupiter | Saturn | Uranus | Neptune |
|---|---|---|---|---|---|
| $H_2$ | 84 | 86.4 | 97 | 83 | 79 |
| He | 16 | 13.6 | 3 | 15 | 18 |
| $CH_4$ | 0.07 | 0.2 | 0.2 | 2 | 3 |

Values are by number of molecules

# Gain/Loss Processes of Atmospheric Gas

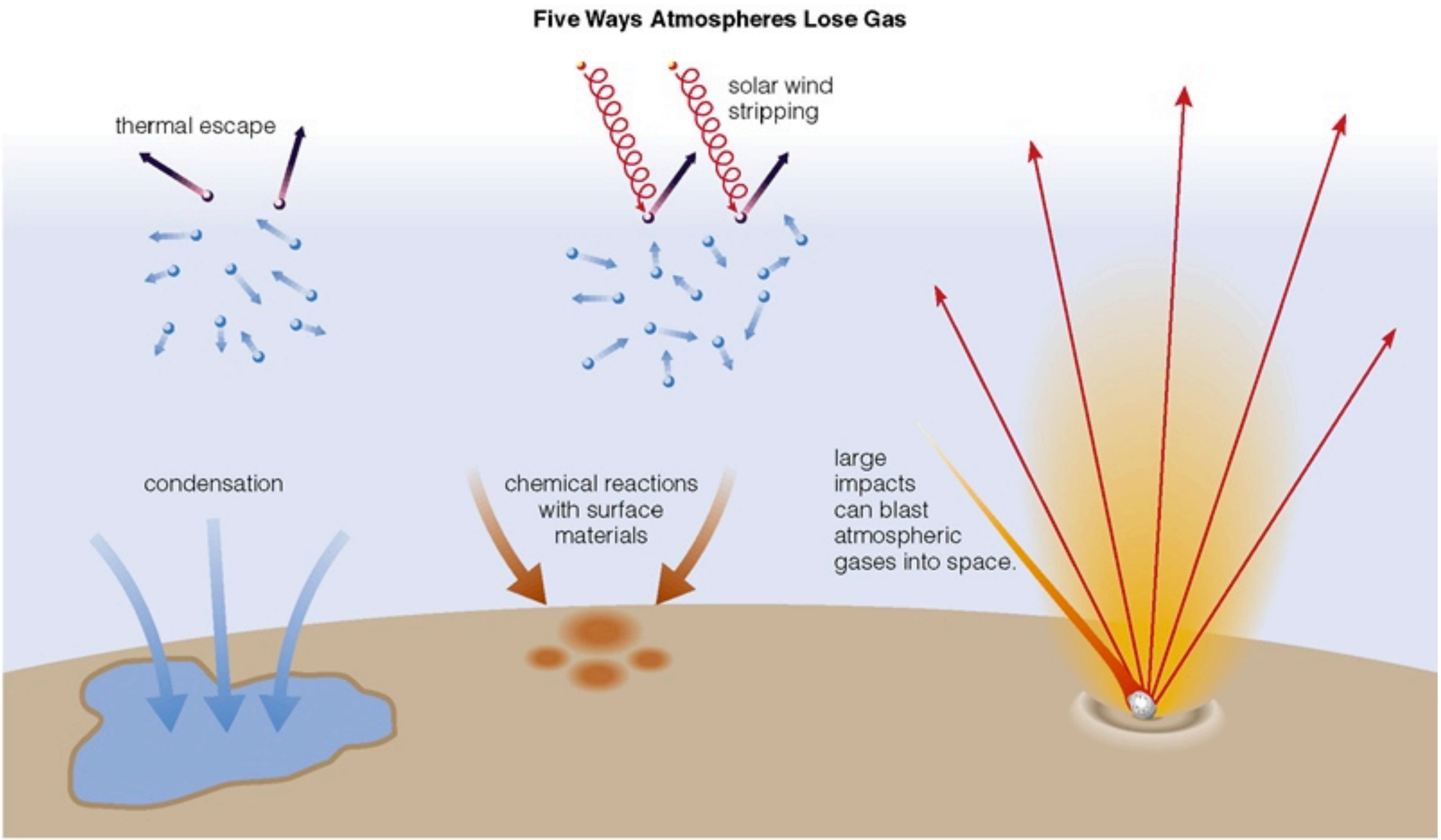


# Gain/Loss Processes of Atmospheric Gas

- Unlike the Giant Planets, the Terrestrials were too small to capture significant gas from the Solar nebula
  - What gas they did capture was H & He, and it escaped
  - Present-day atmospheres must have formed at a later time
- Sources of atmospheric gas:
  - **outgassing** – release of gas trapped in interior rock by volcanism
  - **evaporation/sublimation** – surface liquids or ices turn to gas when heated
  - **bombardment** – micrometeorites, Solar wind particles, or high-energy photons blast atoms/molecules out of surface rock

    (Important factor only if the planet has no substantial atmosphere already)

# Gain/Loss Processes of Atmospheric Gas



# Gain/Loss Processes of Atmospheric Gas

- Ways to lose atmospheric gas:
  - **condensation** – gas turns into liquids or ices on the surface when cooled
  - **chemical reactions** – gas is bound into surface rocks or liquids
  - **stripping** – gas is knocked out of the upper atmosphere by Solar wind particles
  - **impacts** – a comet/asteroid collision with a planet can blast atmospheric gas into space
  - **thermal escape** – lightweight gas molecules are lost to space when they achieve escape velocity

Permanent Removal Processes

# Atmospheric Loss: Jeans Escape

- Atmospheres can lose atoms from stratosphere, especially low-mass ones, because they exceed the escape velocity (Jeans escape or Thermal Escape)
- Escape velocity $v_e = (2GM / R)^{1/2}$
- Mean molecular velocity (thermal speed) $v_o = (2kT / m)^{1/2}$
- Maxwell-Boltzmann distribution – negligible numbers of atoms with velocities > 4 x $v_o$
- Molecular hydrogen, 900 K, 3 x $v_o$= 11.8 km/s
- Jupiter $v_e$=60 km/s, Earth $v_e$=11 km/s
- H cannot escape gas giants like Jupiter, but is easily lost from lower-mass bodies like Earth or Mars
- A consequence of Jeans escape is isotopic fractionation – heavier isotopes will be preferentially enriched as light ones are more easily lost

# Jeans Escape

Maxwell-Boltzmann Distribution for velocities (speeds) of particles of a gas:

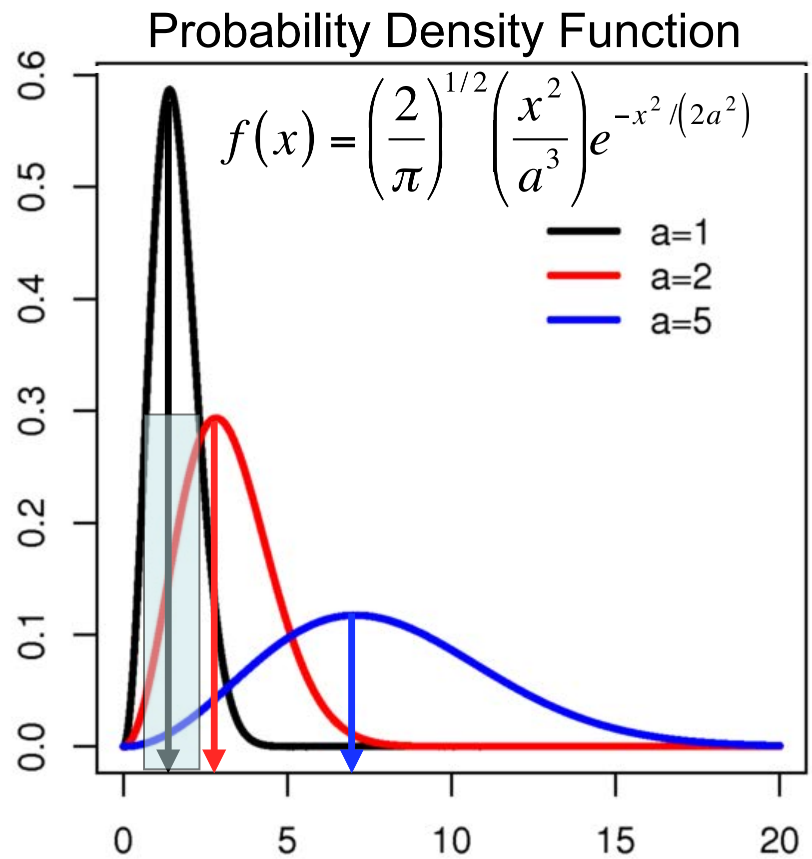
$$f(v)dv = N\left(\frac{2}{\pi}\right)^{1/2}\left(\frac{m}{kT}\right)^{3/2} v^2 e^{-mv^2/(2kT)}dv$$

$$E = \frac{1}{2}mv^2 = kT \text{ (average)}$$

$$v_{th} = v_m = \bar{v}_o = \sqrt{2kT/m}$$

$$Mode = a\sqrt{2} = v_{th}$$

$$FWHM = 2a\sqrt{2\ln 2} \approx 2.355a$$
$$= 2v_{th}\sqrt{\ln 2} \approx 1.665v_{th}$$



# Jeans Escape

The Escape Parameter determines the level of Thermal (Jeans) Escape, and is obviously mass dependent:

$$\lambda_{esc} = \frac{GMm}{kT(R+z)} = \frac{R+z}{H(z)} = \left(\frac{v_e}{v_o}\right)^2$$

$$v_e = \sqrt{\frac{2GM}{r}}$$

$$v_o = \sqrt{2kT/m}$$

$$H(z) = \frac{kT}{g(z)m} = \frac{kTr^2}{GMm}$$

Note that ***larger*** values of the Escape Parameter ➔ ***less*** loss!

# Jeans Escape

Integrating the upward flux in a Maxwellian distribution above the exobase (i.e. the altitude where the mean free path is ≈ the scale height H; below this any upward-moving particles would collide before escaping):

$$\Phi_J = \frac{N_{ex} v_o}{2\sqrt{\pi}} \left(1 + \lambda_{esc}\right) e^{-\lambda_{esc}}$$

Where $N_{ex}$ is the number density of atmospheric molecules at the exobase ≈ $10^5$ cm$^{-3}$ at Earth, $T_{ex}$ ≈ 900 K at Earth

# Atmospheric Loss: Nonthermal Escape

Jeans Escape gives a lower limit on escape flux, but non-thermal processes also play an important role in giving neutrals the excess energy necessary to escape:

- Dissociation & Dissociative Recombination

$$i_2 + h\nu \rightarrow i^* + i^* \;,\; i_2 + e^{-*} \rightarrow i^* + i^* + e^- \;,\; i_2^+ + e^- \rightarrow i^* + i^*$$

- Ion-neutral Reaction

$$i_2 + j^+ \rightarrow ij^+ + i^*$$

- Charge Exchange

$$i + j^{+*} \rightarrow i^+ + j^*$$

- Sputtering
- Electric Fields
- Solar Wind Sweeping

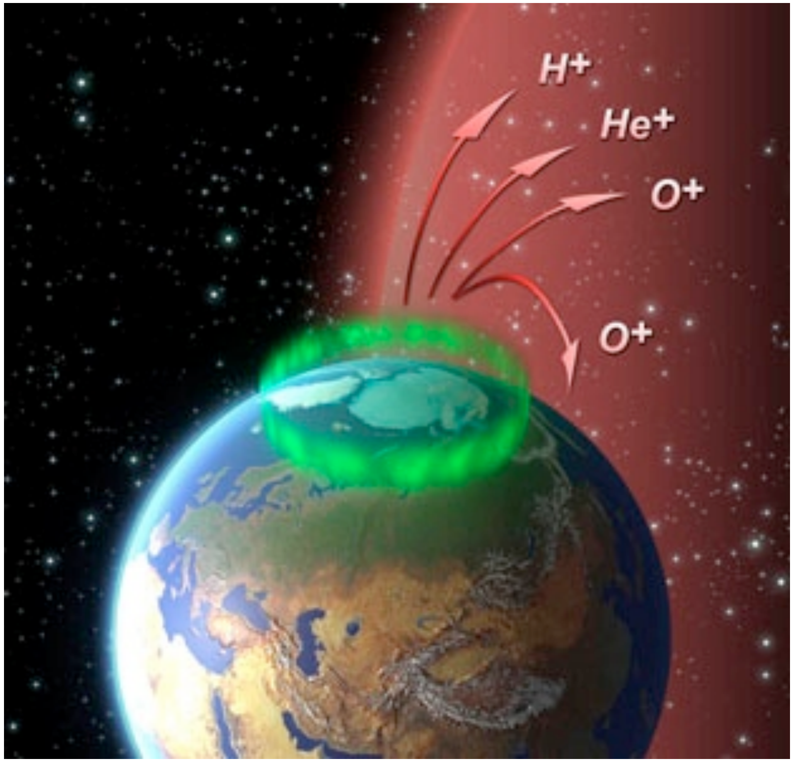
# Atmospheric Loss: Nonthermal Escape

- Sputtering -- Includes elastic or '*knock-on*' collisions of fast ions or atoms with atmospheric atoms, resulting in their escape from the planet's gravitational field. Sputtering encompasses single collision events, cascades of collisions, and even surface collisions where fast ions/ atoms collide with the planet/moon surface and liberate atoms in the case of objects with little to no atmosphere

$$i + j^{+*} \rightarrow i^* + j^{+*} \quad , \qquad i + j^* \rightarrow i^* + j^*$$

Note: If these atoms liberated from the surface do not obtain escape velocity, then they can remain to form an exosphere or corona

# Atmospheric Loss: Nonthermal Escape



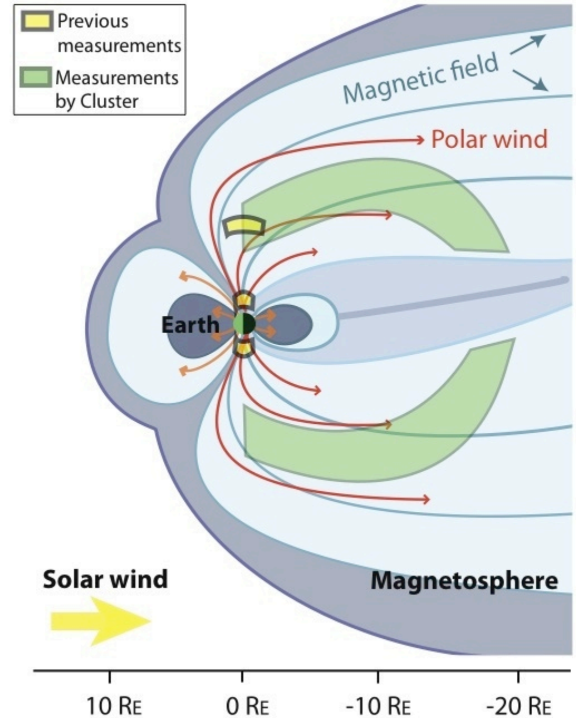
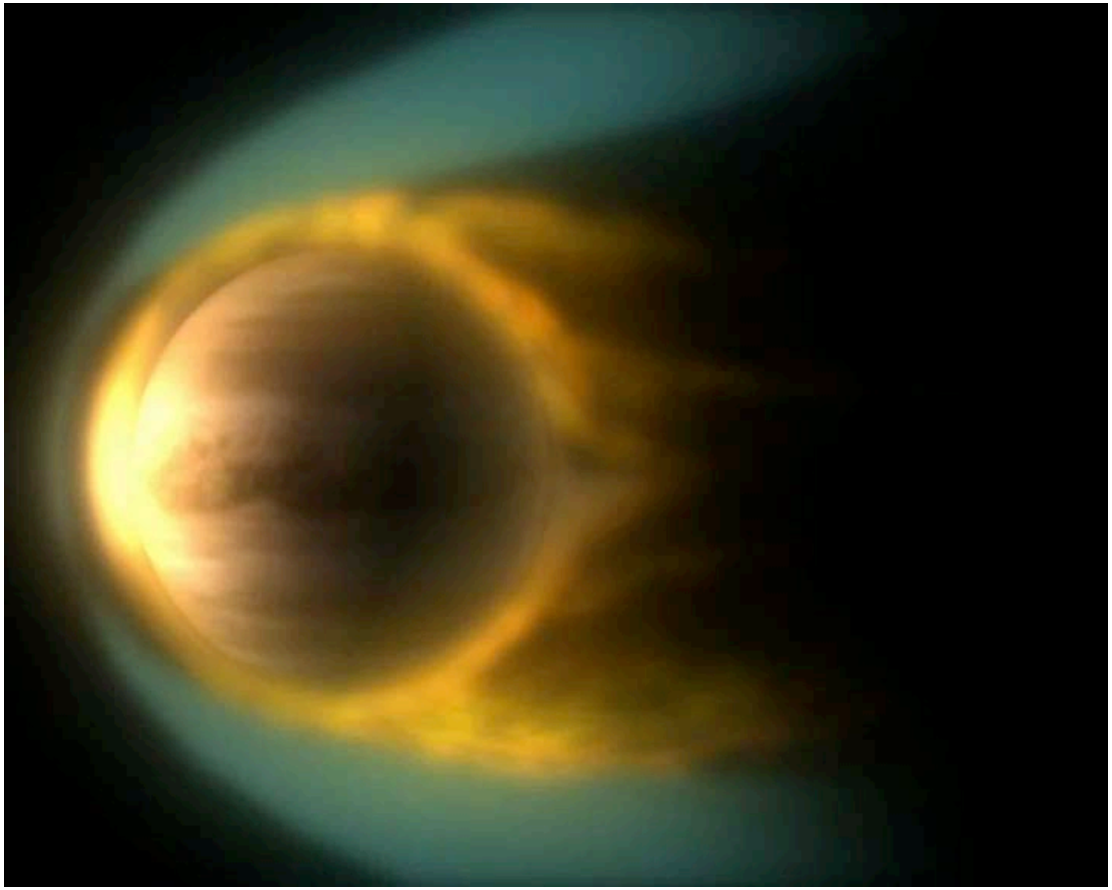




Image Credit: NASA/IRF

- Electric Fields -- Can accelerate charged ionospheric particles away from the planet, or accelerate them into collisions with neutrals (elastic collisions) that result in one or both of the particles exceeding escape velocity. Especially efficient over the polar caps of the Earth where the magnetic fields are open to the solar wind, and parallel electric fields create a 'polar wind' of $H^+$ and $He^+$ ions

# Atmospheric Loss: Nonthermal Escape

- Solar Wind Sweeping -- Occurs in planets/objects without an intrinsic magnetic field where solar wind can directly interact with the atmosphere (both depositing solar wind particles at the subsolar point, and stripping ionospheric particles along the flanks).



# Atmospheric Loss: Blowoff & Impact Erosion

- Hydrodynamic Escape (blowoff) -- Usually occurs in the early solar system and is a means for removing heavier massed atoms from planetary atmospheres where light gas is energetically escaping and entraining heavier atoms into its flow via collisions and drag. Requires significant energy input to the upper atmosphere (such as was present in the early solar system from intense solar wind and increased solar UV flux).

  ** Extrasolar planets

- Impact Erosion -- Dependent on the impactor size. << H and the heat energy is dispersed throughout the volume of atmosphere, >> H and the shock heated air can direct blow out of the atmosphere

# Atmospheric Loss: Blowoff & Impact Erosion

- Impact Erosion -- Dependent on the impactor size. << H and the heat energy is dispersed throughout the volume of atmosphere, >> H and the shock heated air can direct blow out of the atmosphere

  How much is lost?

$$M_e = \frac{\pi R_i^{\,2} P_o \varepsilon_e}{g_P} \quad , \quad \varepsilon_e = \frac{v_i^{\,2}}{v_e^{\,2}\left(1 + \varepsilon_v\right)}$$

Where $R_i$ is the radius of the impactor, $v_i$ is its velocity, $v_e$ is the escape velocity and $\varepsilon_v$ is the evaporative loading parameter of the impactor (~20) and inversely proportional latent heat of evaporation. $P_o/g_P$ = mass/unit area of the atmosphere

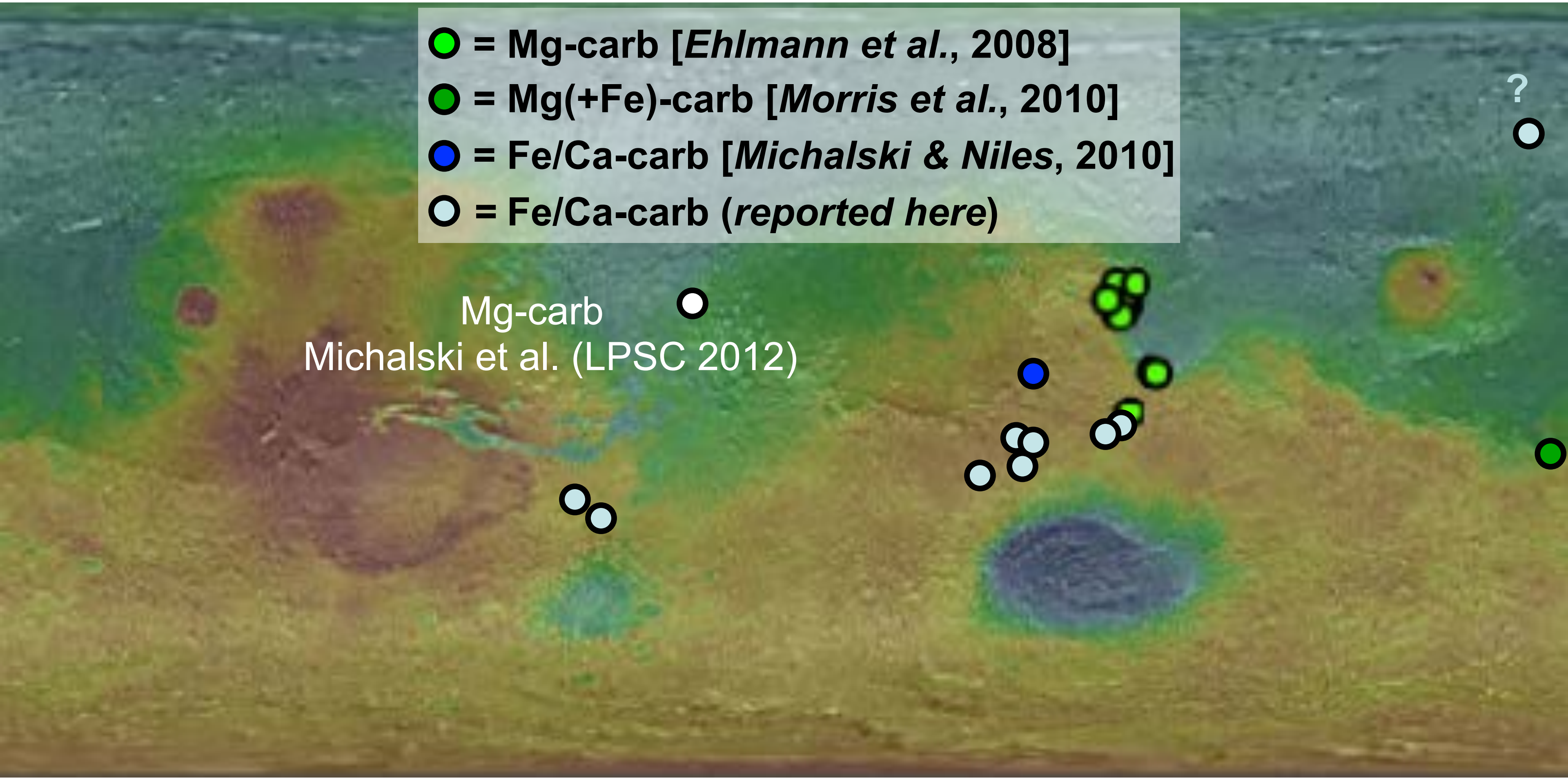
# Atmospheric Evolution

- Earth atmosphere originally $CO_2$-rich, oxygen-free
  (solar/chondritic abundances, geologic record)
- $CO_2$ was progressively transferred into rocks by the Urey reaction (takes place in presence of water):

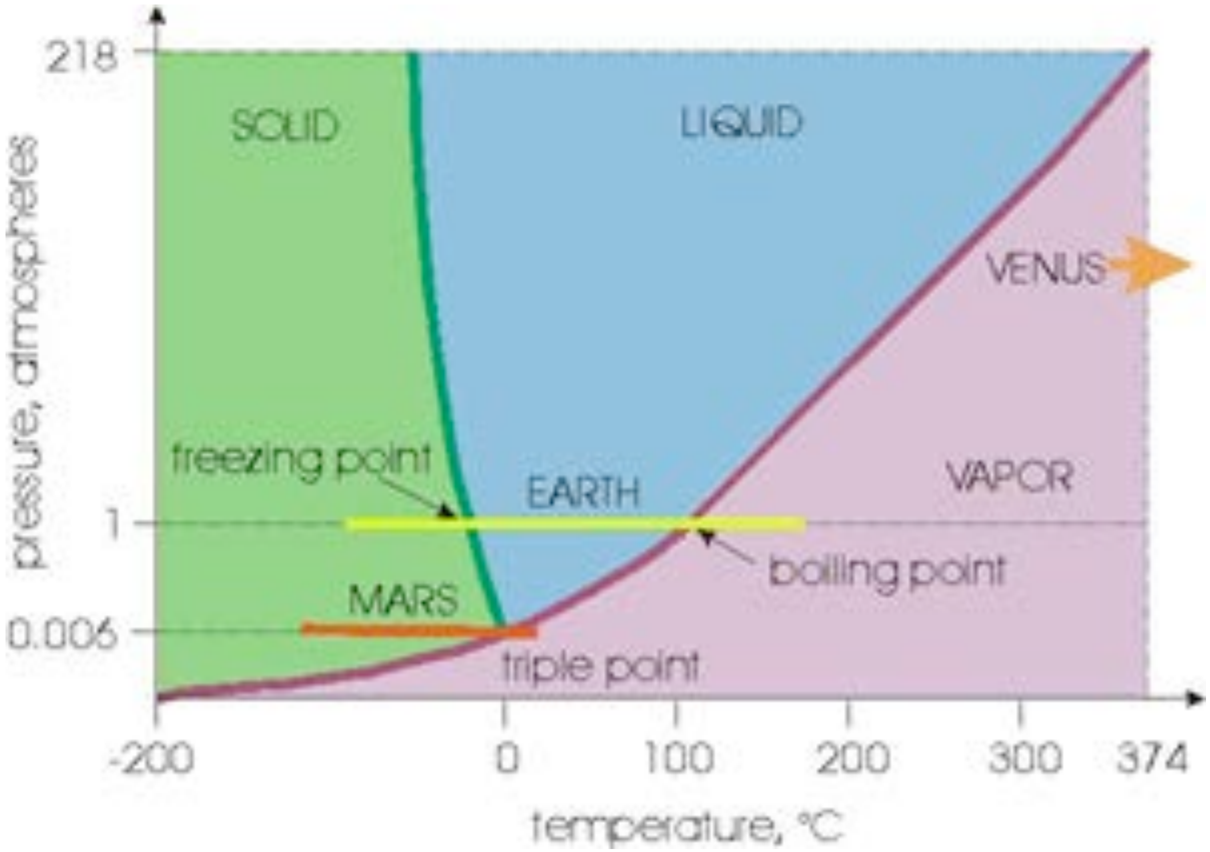
$$MgSiO_3 + CO_2 \rightarrow MgCO_3 + SiO_2$$

- Rise of oxygen began ~2 Gyr ago (photosynthesis & photodissociation)
- Venus never underwent similar evolution because no free water present (greenhouse effect, too hot)
- Venus and Earth have ~ same *total* $CO_2$ abundance
- Urey reaction may have occurred on Mars (water present early on), but little carbonate detected*

# Carbonate-bearing rocks on Mars



# Urey weathering on ancient Mars?




- Mars average atmospheric pressure ***at*** the $H_2O$ triple point
- Coincidence, or carbonate formation until surface water became destabilized (Kahn, 1985)?

# Atmospheric Evolution

We can constrain when the atmosphere of a terrestrial planet (or moon) formed based on isotopic fractionation due to radioactive decay, for example:

$^{40}Ar$ is a product of the radioactive decay of potassium ($^{40}K$) found in the (sub)surfaces of terrestrial planets, whereas $^{36}Ar$ is a primordial and stable isotope incorporated into planetesimals at very cold temperatures.

Both are liberated into the atmosphere when the mineral holding them melts, so based on the half-life of $^{40}K$ and the estimates of primordial potassium and outgassing rates we can infer from the abundance of $^{40}Ar$ relative to $^{36}Ar$ when the bulk of the atmosphere was formed

For Earth it is within the first few 10s of millions of years, so very early

# Summary of Atmospheres

- Surface temperature depends on solar distance, albedo, atmosphere (greenhouse effect)
- Scale height and lapse rate are controlled by bulk properties of atmosphere (and gravity)
- Chemical equilibrium from photochemical reactions determines the atmospheric profile of various constituents
- Coriolis effect organizes circulation into "cells" and is responsible for bands seen on giant planets
- Isotopic fractionation is a good signal of atmospheric loss due to Jeans escape
- Terrestrial planetary atmospheres are *not* primordial – affected by loss and outgassing
- Significant volatile quantities may be present in the interiors of terrestrial planets