# 외계행성 대기
# Exoplanetary Atmospheres

## Lecture 12: Composition of a Planetary Atmosphere II

Clouds, Escape, and Evolution

2026 November 30 (Monday)

**Based on: Chapter 4 of Seager, *Exoplanet Atmospheres* (2010)**

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# Outline – Lecture 12

Basic Cloud Physics

Atmospheric Escape

Atmospheric Evolution

Summary

# What Is a Cloud?

- **Cloud:** a mass of **liquid or solid particles** suspended in a planet's atmosphere. It forms
  - when atmospheric gas **condenses**, or
  - when a **photochemically produced** gas condenses.

- **Words that are easily confused:**
  - **Aerosol:** any particle suspended in the air (smoke, dust, bacteria, cloud drops). Usually means very small particles that do not fall out.
  - **Haze:** very small, opaque particles that reduce visibility and add color. Almost always **photochemically produced**.

- **Why clouds matter:**
  - They control the **albedo**, hence the energy balance (Lecture 3): Earth's water clouds and Venus's sulfuric-acid clouds are very reflective; Jupiter's hazes absorb at short wavelengths.
  - They give **color and variability** (Jupiter's bands, Earth's brightness changes seen from afar).
  - They are tied to **dynamics and temperature**.

# Clouds Are Very Diverse

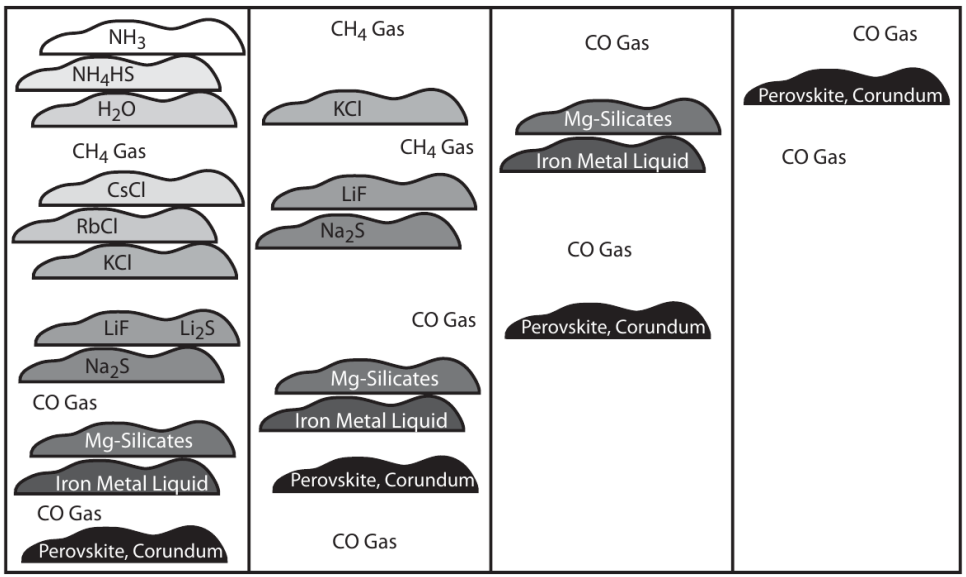



Figure 1: Cloud layers in giant planets, from Jupiter (left) to hotter planets (right). Seager (2010), Fig. 4.10.

- **Earth:** water drops or ice crystals, 10–100 $\mu$m.
- **Titan:** probably liquid methane.
- **Hot Jupiters:** liquid iron droplets, solid silicates, . . .
- **Layered:** one planet can have several decks, one for each condensable gas.
- **Hotter planet $\rightarrow$ same cloud higher up.** Silicate and iron clouds on hot Jupiters are like those deep inside Jupiter, where it is equally hot.

# Clouds: A Blessing and a Problem

**Blessing: what clouds tell us**

- The **temperature** where they form.
- Possibly the **rotation rate**, if cloud patterns are fixed.

**Problem: why they are hard**

- They **block the light** from layers below, weakening spectral features.
- Cloud height, condensed fraction, and particle sizes are **hard to predict**.
- **Radiative transfer** through clouds is hard.

- **Models range** from full cloud-formation calculations to simply **prescribing** the cloud height, density, and particle size.
- Most models assume **complete, homogeneous cloud cover** (possibly unrealistic).
- Haze was detected on HD 189733b with the Hubble Space Telescope.

# Where Do Clouds Form? Saturation

- **Everyday picture (Earth):** warm, moist air rises, **expands and cools**. When the vapor is cold enough, it condenses into a cloud.
- **Condition for condensation:** the gas partial pressure exceeds the **saturation vapor pressure** $P_V$ (the partial pressure when the air is exactly saturated):

$$\boxed{P_g(T) = X_g\, P(T) \;\geq\; P_{V,g}(T)}$$

  - $P$ = total gas pressure, $X_g$ = mixing ratio of gas $g$.
- **Cloud base:** where the planet's $T$–$P$ profile crosses the saturation curve $P_V(T)$.
- The curve $P_V(T)$ (for each gas) is the **Clausius–Clapeyron curve**. We derive its form next.

# The Clausius–Clapeyron Curve

- From the first and second laws, the saturation pressure changes with temperature as

$$\frac{\mathrm{d}P_V}{\mathrm{d}T} = \frac{L}{T\,(V_2 - V_1)}$$

  $L$ = specific latent heat ($\mathrm{J\,kg^{-1}}$), $V = 1/\rho$ = specific volume, subscript 1 = liquid or solid, 2 = vapor.

- **Two simplifications:** the vapor is an **ideal gas**, and the liquid/solid volume is tiny, $V_2 - V_1 \approx V_2 = R_V T/P$:

$$\boxed{\frac{\mathrm{d}P_V}{\mathrm{d}T} = \frac{L P_V}{R_V T^2}}$$

  ($R_V$ = specific gas constant of the vapor).

- **Meaning:** $P_V$ rises **very steeply** with $T$. Hence a small cooling can condense a lot of vapor.

- Including a temperature-dependent $L$ gives the general curve $\ln P_V = \ln C + \frac{1}{R_V}\left(-\frac{L_0}{T} + \Delta\alpha \ln T + \frac{\Delta\beta}{2} T\right)$ with constants tabulated in Seager's Table A.6.

# Finding the Cloud Base

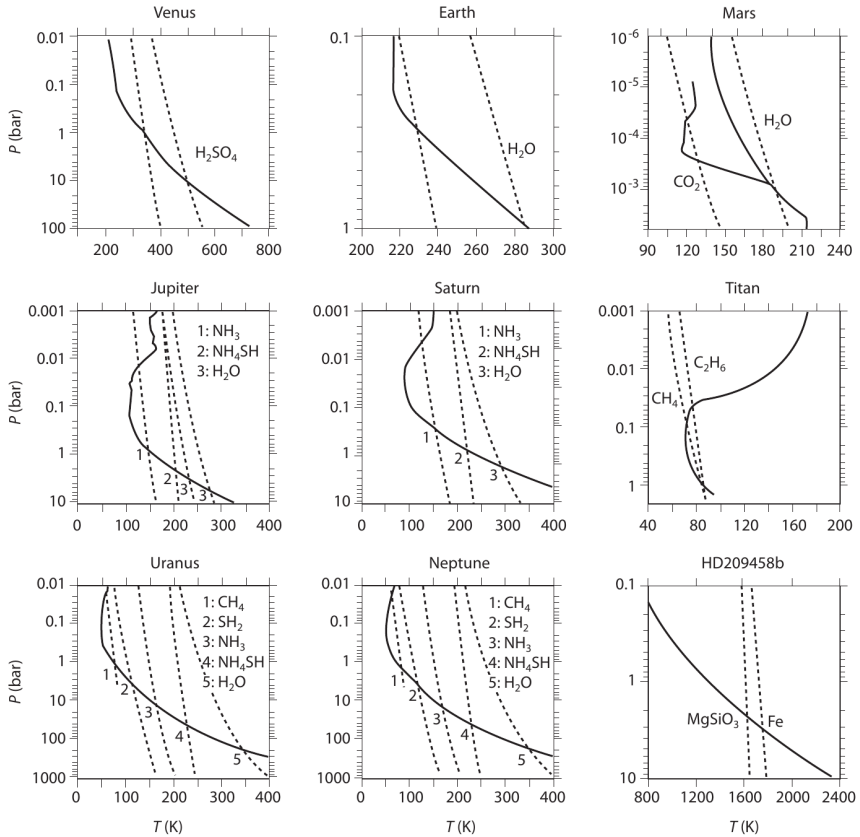



Figure 2: Saturation curves (dashed) versus planetary $T$–$P$ profiles (solid). Seager (2010), Fig. 4.11.

- **Cloud base** = intersection of a dashed curve and the solid profile.
- **A great variety of clouds** follows from different $T$, $P$, and composition:
  - Earth: $H_2O$; Venus: $H_2SO_4$,
  - Jupiter: $NH_3$, $NH_4SH$, $H_2O$,
  - HD 209458b: $MgSiO_3$ and Fe.
- **Caveat:** the picture assumes 100% humidity above the base. Real clouds need **condensation nuclei** (dust, soot on Earth). For exoplanets the nuclei are **unknown**.

# How Thick Is a Cloud?

- **Idea:** above the cloud base the atmosphere cools, so $P_V$ falls and the excess vapor condenses. Integrate Clausius–Clapeyron with constant $L$ from the base temperature $T_c$:

$$P_V(T) = P_V(T_c)\exp\left[-\frac{L(T_c - T)}{R_V\, T\, T_c}\right]$$

- Use $T\,T_c \approx T_c^2$ and the convective lapse rate $\mathrm{d}T/\mathrm{d}z = -g/c_p$ (Lecture 9), so $T_c - T = (g/c_p)(z - z_c)$:

$$\boxed{P_V(T) = P_V(T_c)\,\mathrm{e}^{-(z-z_c)/H_c}, \qquad H_c = \frac{R_V\, T_c^2\, c_p}{g\, L}}$$

- $H_c$ **= cloud scale height:** the distance over which the saturation pressure (and so the cloud density) drops by $e$.

- **Compare with the atmospheric scale height** $H = R_s T/g$: typically $H_c/H \approx 0.05$–$0.2$.
  - **Earth:** $H \approx 8$ km, $H_c \approx 1.5$ km. **Jupiter:** $H \approx 43$ km, $H_c \approx 7$ km.

- **Conclusion:** an atmosphere spans $\sim 5$–$10$ scale heights, so cloud layers are **vertically thin**.

# Cloud Density and Cloud Formation Models

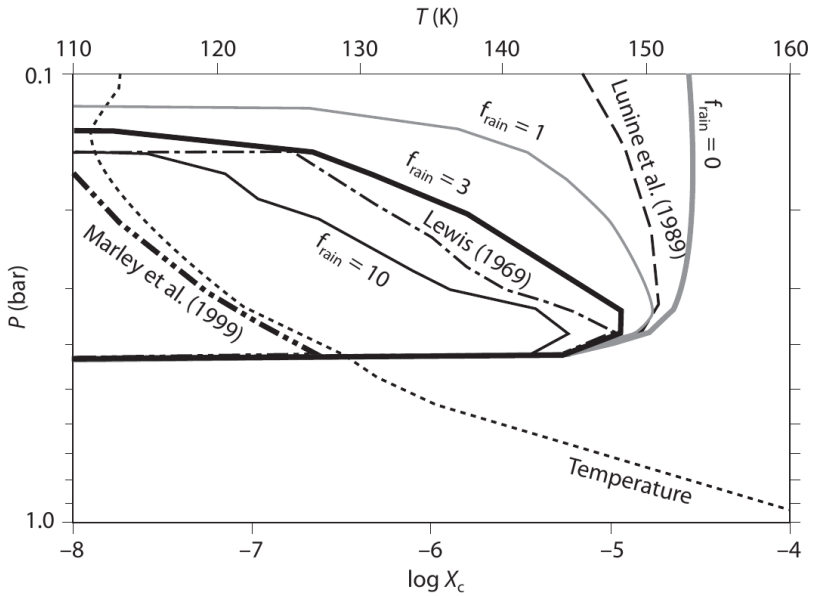



Figure 3: Cloud-particle mixing ratio versus pressure in Jupiter's ammonia cloud, for different models. Seager (2010), Fig. 4.12.

- **Upper limit on cloud density:** assume **all** the vapor condenses. Density = condensate mass / cloud volume.
- **Real predictions are hard**, even for Earth. Exoplanets have no in-situ data, so **simple 1D models** are used.
- **Growth vs. destruction:**
  - growth: convective uplift of vapor, nucleation, coagulation, coalescence,
  - destruction: **gravitational sedimentation** (rain-out).
- **Goal:** the fraction of gas condensed and the particle size at each altitude (horizontally uniform clouds).

# Cloud Particle Sizes

- **Why size matters:** it sets how much light is **absorbed** and in which **direction it is scattered** (Lecture 10).
- **Solar-system examples:**
  - Venus: clouds $r \approx 0.85$–$1.15\,\mu$m; haze above $r \approx 0.2\,\mu$m.
  - Jupiter: upper haze $r \approx 0.5\,\mu$m; deep decks up to tens of $\mu$m.
- **Not one size:** particles follow a **size distribution** (gamma, log-normal, or power law).
  - Earth's liquid-water clouds: $n(a) \propto \left(\frac{a}{a_0}\right)^6 \exp\left[-6\,\frac{a}{a_0}\right], \quad a_0 \approx 4\,\mu$m.
  - Earth's stratospheric aerosols: $n(a) \propto \left(\frac{a}{a_0}\right)^{1/2} \exp\left[-2\,\frac{a}{a_0}\right]$.
- The **optical properties** of these particles are the topic of Mie theory (Lecture 10).

# Why Does Escape Matter?

- **1. It sets the bulk composition** (or whether an atmosphere exists at all).
  - Hot super-Earths very close to their star may have lost everything (like Mercury).
  - Some Earth-like planets may have lost their primordial hydrogen.
  - Some hot Neptunes may be **remnant cores** of giants that lost their H/He.
- **2. It is a continual sink of light gases**, important for photochemistry.
- **Three stages of escape:**
  1. transport of gas to the upper atmosphere,
  2. conversion to the escaping form (usually atoms or ions),
  3. the escape itself.

  Any stage can be the **bottleneck**.
- **Three types:** thermal **hydrostatic** (Jeans), thermal **hydrodynamic**, and **nonthermal**.

# The Star Drives the Escape

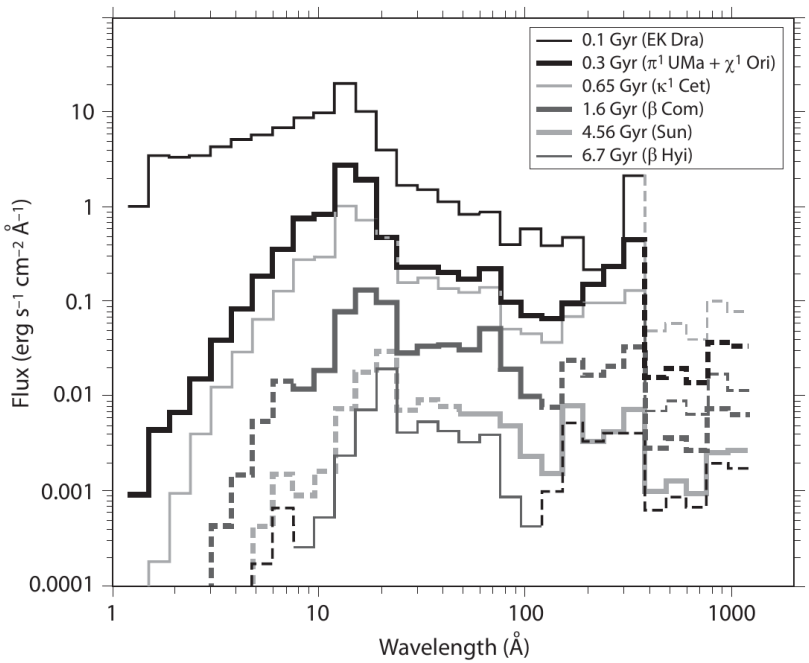



Figure 4: Spectra of Sun-like stars at different ages. Seager (2010), Fig. 4.13.

- **EUV radiation heats the upper atmosphere** and drives escape.
- **Young stars are far more active:** the UV flux of a 100 Myr old Sun-like star was up to **1000 times** today's. (At visible wavelengths the early Sun was only $\sim 30\%$ fainter.)
- **Hard to know:** the EUV and stellar-wind **history** of any given star is not measured and must be estimated. EUV is absorbed by the interstellar medium, so even telescopes see only nearby stars.
- The **stellar wind** matters mainly for nonthermal escape.

# Thermal Escape: A Simple Criterion

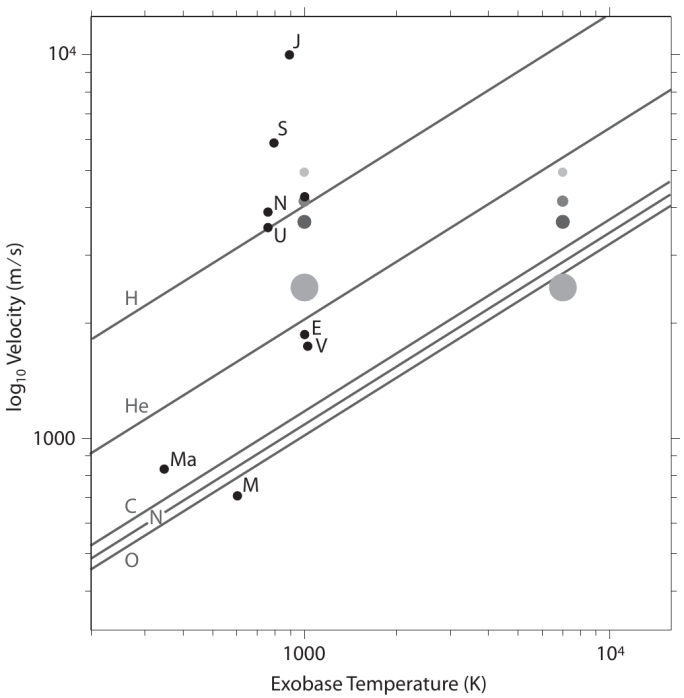



Figure 5: Thermal speed of atoms versus $1/6$ of each planet's escape speed. Seager (2010), Fig. 4.14.

- **Idea:** a particle escapes if its **thermal speed exceeds the escape speed**. Since only the fast tail escapes, include a factor $1/6$:

$$\sqrt{\frac{2k_{\mathrm{B}}T_{\mathrm{exo}}}{m}} > \frac{1}{6}\sqrt{\frac{2GM_p}{R_p}}$$

- **Where:** in the **exosphere**, whose bottom is the **exobase**, the height where particles no longer collide (mean free path $>$ scale height). So $T$ is the **exobase temperature**.

- **Lessons from the plot:**
  - **Light atoms** (H, He) escape much more easily than C, N, O.
  - **Massive planets** (Jupiter, Saturn) cannot lose H, no matter how hot.

# Jeans Escape: "Evaporation" From the Exobase

- **Picture:** speeds follow a **Maxwellian** distribution. Particles in the **high-speed tail**, moving upward at the exobase, escape. Slower particles then refill the tail.
- Integrating over the escaping particles gives the **Jeans escape flux**:

$$\boxed{\Phi_{\text{Jeans}} = B\,\frac{n_c}{2\sqrt{\pi}}\sqrt{\frac{2k_{\text{B}}T_c}{m}}\,(1+\lambda_c)\,\mathrm{e}^{-\lambda_c}}$$

  ($n_c$, $T_c$ at the exobase; $B \sim 0.5$–$0.8$ accounts for the slow refilling of the tail).

- **Escape parameter:**

$$\lambda_c = \frac{GM_p\,m}{k_{\text{B}}T\,r_c} = \frac{E_{\text{esc}}}{k_{\text{B}}T_c} = \frac{r_c}{H}, \qquad E_{\text{esc}} = \tfrac{1}{2}mv_{\text{esc}}^2.$$

- **Meaning:** $\lambda_c$ compares gravitational binding energy with thermal energy. Because of $\mathrm{e}^{-\lambda_c}$, the flux is **extremely sensitive** to $\lambda_c$: **large** $\lambda_c \Rightarrow$ **almost no escape**.
- To judge if a gas was depleted, compare the depletion time (original amount / flux) with the age, and include any production.

# Hydrodynamic Escape

- **What:** escape so fast that the atmosphere flows outward **like a fluid**, as strong stellar heating makes the particles too energetic for gravity to hold.
- **Needs a lot of EUV** to push the gas out against gravity: high exospheric temperature and strong EUV flux.
- **Heavy elements (C, N, O) can be dragged along** with escaping H.
- **Typically an early-history event.** Today, Pluto ($CH_4$, $N_2$) is probably the only solar-system body in significant hydrodynamic escape.
- **Which regime?** Use the Jeans parameter:
  - $\lambda_c \gg 1$: safely **Jeans (hydrostatic)** escape.
  - $\lambda_c \lesssim 1$: hydrodynamic escape is possible. It is necessary but not sufficient: model calculations are needed.
- **Signature:** a temperature that **decreases** with height near the exobase (adiabatic cooling by the outflow beats the heating).

# Energy-Limited Escape: How Long Does an Atmosphere Last?

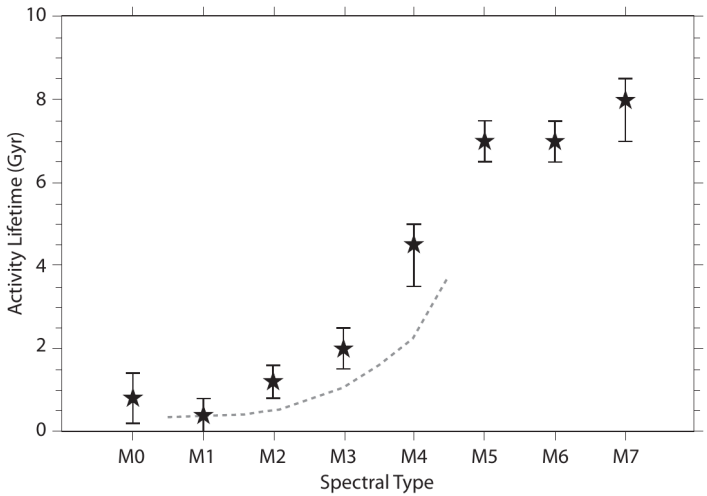



Figure 6: Activity lifetimes of M stars. Seager (2010), Fig. 4.15.

- **Energy budget:** gravitational energy to lift the atmosphere vs. the EUV power received.

$$E_p = -\frac{GM_p\, m_{\rm atm}}{\beta R_p}, \qquad P_{\rm UV} = \pi R_p^2\, F_{\rm EUV}$$

- With a heating efficiency $\eta < 1$ ($\beta > 1$ = exosphere size in units of $R_p$), the **lifetime** is

$$\tau \sim \frac{G}{\pi}\,\frac{M_p\, m_{\rm atm}}{R_p^3\,\beta\,\eta\,\langle F_{\rm EUV}\rangle}$$

- **Big uncertainties:** the initial atmosphere mass (1% to 20% of the planet mass) and the EUV flux, which was up to thousands of times higher early on, $\propto (t_0/t)^{5/6}$.
- **M stars** stay active for **billions of years**, so super-Earths around them are most at risk.

# Earth's Upper Atmosphere: Thermosphere and Exosphere

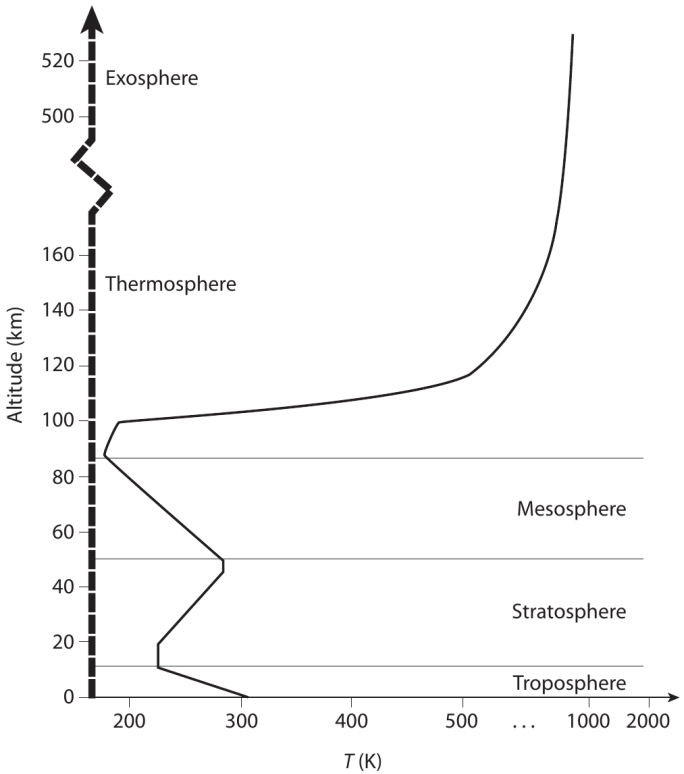



Figure 7: Earth's temperature profile with the thermosphere and exosphere. Seager (2010), Fig. 4.16.

- **Thermosphere:** the temperature **rises sharply** (EUV heating of very thin gas) to $\sim$ 1000 K or more.
- **Exosphere:** the top layer (to $\sim$ 500 km for Earth) where escape actually occurs.
- **Real calculations** solve the fluid equations for the thermosphere and exosphere, and need the star's EUV and the planet's upper-atmosphere composition: these are **often unknown** for exoplanets.

# Nonthermal Escape

- **What:** collisions and reactions that give atoms **enough energy to escape even when the gas is cold**. It lets **heavier atoms (N, C, O)** escape.
- **Which one dominates** depends on exospheric temperature, **magnetic field**, planet–star distance, star type, and escape speed.

| **Process** | **Idea** | **Where** |
|---|---|---|
| Charge exchange | energetic ion hands its energy to a neutral atom | Earth (H, D) |
| Dissociative recombination | molecular ion + electron $\rightarrow$ energetic atoms | Mars (O) |
| Photodissociation | excess photon energy becomes kinetic energy | Venus (H), Titan |
| Ion escape (polar wind) | ions leave along open magnetic field lines | Earth poles |
| Sputtering, knock-on | impacts cause a cascade of collisions | Io, Mercury |
| Solar-wind pickup | wind's magnetic field sweeps up ions | planets without a field |

A global magnetic field (as on Earth) **shields** the atmosphere by deflecting the solar wind.

# Earth's Atmospheric Evolution

- **Birth:** volcanic outgassing gave mostly $CO_2$ and $N_2$, with $H_2O$ and some $NH_3$, $CH_4$, $H_2$.
- **Hydrogen:** lost by escape, probably within hundreds of Myr. Outgassing keeps $\sim$ 100–1000 ppmv of $H_2$ even today.
- **$CO_2$:** dissolved in the ocean and became carbonates, so the air went from $CO_2$-dominated to $< 1\%$.
- **$O_2$ rise ($\sim$ 2.4 Gyr ago):** produced **only by life** (cyanobacteria began $\sim$ 300 Myr earlier). It first reacted with surface rocks, and stayed far below 21% until $\lesssim$ 0.6 Gyr ago.
- **$N_2$:** inert, left over from outgassed ammonia and impacts.
- **Today:** 20.9% $O_2$, 78.1% $N_2$, 0.93% Ar.

# Venus and Mars: Two Different Fates

**Venus: runaway greenhouse**

- Early Venus was like Earth, with an ocean tens to hundreds of meters deep.
- Water evaporated, **EUV split $H_2O$**, and H escaped (hydrodynamic escape, $< 2 \times 10^9$ yr).
- The oxygen was dragged away or locked in crustal minerals.
- No ocean to store $CO_2 \Rightarrow \sim 100\times$ more $CO_2$ than Earth.
- No magnetic field: a strong young solar wind could add to the loss.

**Mars: massive loss**

- Early Mars had liquid water, so a thicker atmosphere (1–3 bar vs. 6 mbar today) with greenhouse gases.
- Low gravity and a magnetic field lost after $\sim 700$ Myr, plus strong early EUV and solar wind, made large loss possible.
- Giant impacts may have eroded air.
- Timescales need models of the early Sun and Mars.

**Take-away:** similar starting points led to very different atmospheres because of distance from the Sun, planet mass, and magnetic field.

# What About Exoplanets?

- **Huge range of possibilities:** exoplanets span almost all masses and orbital distances (Lecture 1), so escape and evolution can differ enormously.
- **Unknowns:** present composition, the star's history, original atmosphere mass and composition, whether there is a magnetic field. Solar-system planets have **isotope patterns** that record escape histories, which we cannot measure for exoplanets.
- **What we can observe:**
  - the **bulk composition** of the lower atmosphere,
  - **escaping gas** in an extended exosphere. HD 209458b shows neutral H in Lyman-$\alpha$ absorption during transit; the estimated loss is $\sim$ few $\times 10^{10}$ g s$^{-1}$, i.e. $< 1\%$ of the planet's mass over its life.
- **Why can hot Jupiters keep their atmospheres?** They are **massive** (hundreds of Earth masses). Some hot Neptunes and super-Earths may be **remnant cores**.

# Summary: Clouds, Escape, and Evolution

- **Clouds** form where the planet's $T$–$P$ profile crosses the **saturation curve** $P_g = X_g P \geq P_V$:

$$\frac{\mathrm{d}P_V}{\mathrm{d}T} = \frac{LP_V}{R_V T^2}, \qquad H_c = \frac{R_V T_c^2 c_p}{gL} \;\Rightarrow\; \frac{H_c}{H} \approx 0.05\text{–}0.2 \text{ (thin layers)}.$$

  Cloud sizes follow a **distribution**; hazes come from **photochemistry**.

- **Escape** sets the bulk composition. Thermal escape needs a large **thermal speed vs. escape speed**, quantified by $\lambda_c = GM_p m/(k_\mathrm{B} T r_c)$:
  - **Jeans** ($\lambda_c \gg 1$): tail of the Maxwellian, flux $\propto (1+\lambda_c)\mathrm{e}^{-\lambda_c}$,
  - **Hydrodynamic** ($\lambda_c \lesssim 1$): EUV-driven outflow; lifetime $\tau \sim GM_p m_\mathrm{atm}/(\pi R_p^3 \beta \eta \langle F_\mathrm{EUV}\rangle)$,
  - **Nonthermal**: ions, charge exchange, solar-wind pickup; magnetic fields protect.

- **Evolution:** Earth (life makes $O_2$), Venus (runaway greenhouse), Mars (massive loss) show how escape plus distance, mass, and magnetic field shape an atmosphere.

- **For exoplanets:** we mostly see the composition after early evolution, so we focus on the present atmosphere.