# ASTR 405
# Planetary Systems
# Exoplanet Atmosphere

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Supplementary Readings: **atmosphere.pdf** on Canvas

*Exoplanet Atmospheres by Sara Seager and Drake Deming*

# Modules

- Part I: Exoplanet Detection Methods
  - Explore the techniques astronomers use to discover planets beyond our solar system
- Part II: Exoplanet Demographics and Planet Formation
  - Investigate the statistical properties of exoplanets and theories of how planetary systems form
- **Part III: Exoplanet Atmospheres, Interiors, and Characterization**
  - **Examine methods for studying the physical properties and compositions of distant worlds**

# Module III: Exoplanet Atmospheres, Interiors, and Characterization

- **Exoplanet Characterization**
  - Transmission, emission & phase curves → atmospheric composition, P-T profile
  - Rossiter–McLaughlin effect → spin–orbit angles
- **Atmospheric Physics**
  - <u>Hydrostatic structure and P-T profiles</u>
  - <u>Thermodynamics: convection, lapse rate, and radiative balance</u>
  - Composition and clouds: metallicity, C/O ratio, disequilibrium chemistry
  - Atmospheric loss and the cosmic shoreline
- **Planetary Interiors**
  - Giant planets: phase diagram of hydrogen, central pressure, Hot Jupiter radius inflation
  - Terrestrial planets: heat transport, cooling, and mass–radius relation

# Atmosphere Scale Height

Recall the hydrostatics balance of protoplanetary disks, the exoplanet atmosphere in hydrostatic equilibrium can be expressed as

$$\frac{dp}{dz} = -\rho g \ .$$

From ideal gas law, $p = \rho RT$, and assume an **isothermal** atmosphere, we get

$$p = p_0 e^{-z/H} ,$$

Atmospheres are not exactly isothermal

where the scale height is $\boxed{H = \dfrac{RT}{g}}$.

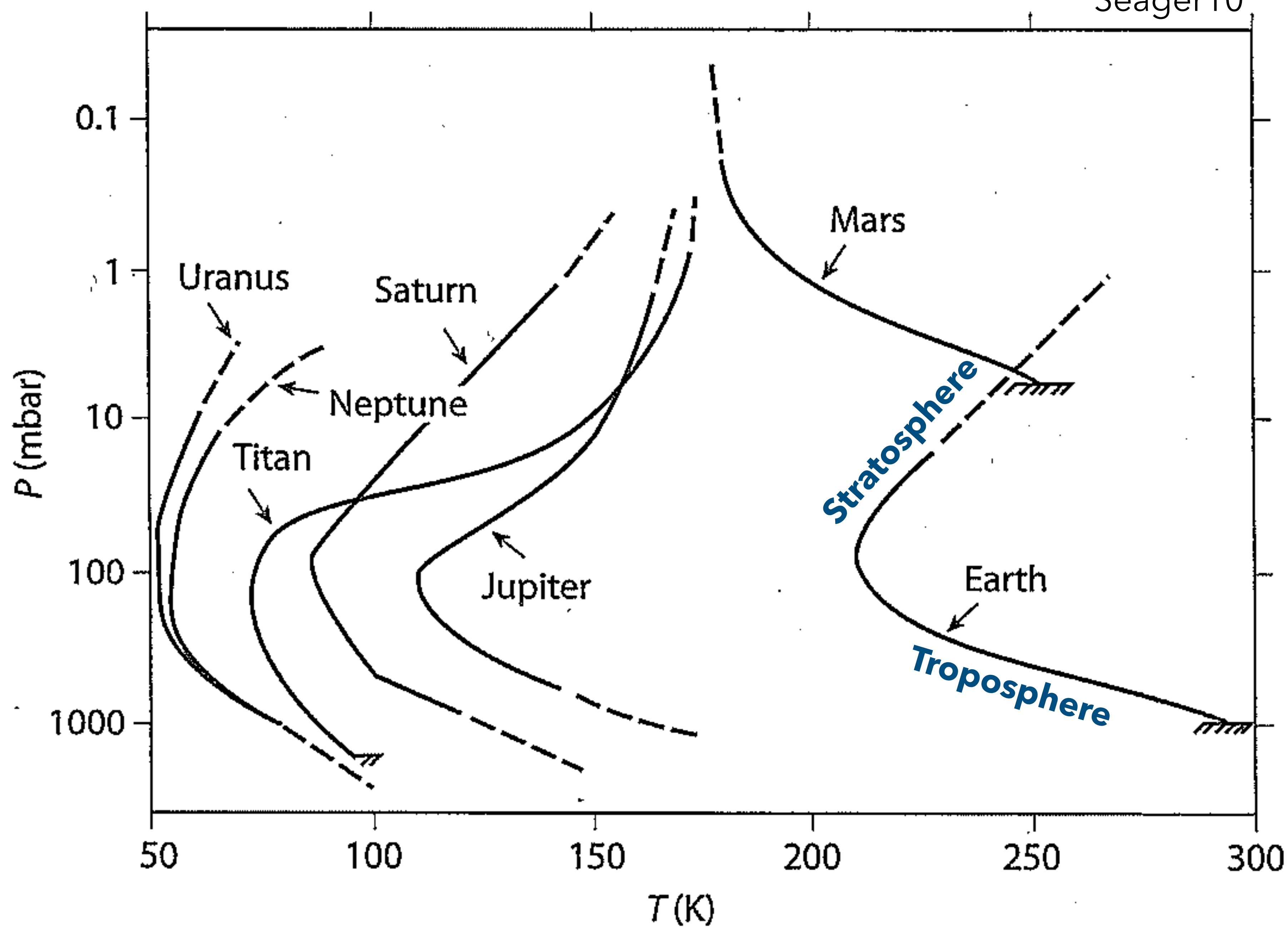
$R = \dfrac{R_u}{\mu}$ is the **specific gas constant**, which depends on the gas composition.

$R_u = 8.3145 \ \mathrm{J\,mol^{-1}\,K^{-1}}$ is the universal gas constant and $\mu$ is the mean molecular weight (in $\mathrm{g\,mol^{-1}}$).

# Pressure-Temperature (P-T) Profiles

Atmospheric pressure-temperature profiles of planets in our Solar System with significant atmospheres (troposphere + stratosphere).

Seager10



# Energy Budget and the First Law of Thermodynamics

- Tracking how temperature changes in an atmosphere requires following the energy budget of an air parcel, i.e., how energy is gained, lost, or transformed between heat and work.
- The First Law of Thermodynamics expresses this energy conservation: The change in a system's internal energy equals the heat added minus the work done by the system.
- **For a parcel of gas:**

$$\boxed{\frac{dU}{dt} = Q - p\frac{dV}{dt}}$$

or equivalently (using enthalpy $H = U + pV$)

$$\frac{dH}{dt} = Q + V\frac{dp}{dt}$$

$U$ is internal energy, $Q$ is heat added to the system, $p\,dV$ is work done by the system during expansion.

# Atmospheric Application of the First Law

The First Law: $\boxed{dU = \delta Q - pdV}$ and $\delta Q = 0$ (the process is adiabatic, no heat exchange)

For an air parcel moving vertically:

- Rising parcel
  - Ambient pressure drops → parcel expands $(dV > 0)$
  - Does work on surroundings → internal energy ↓, temperature ↓ → adiabatic cooling
- Sinking parcel
  - Ambient pressure increases → parcel compresses $(dV < 0)$
  - Work done on parcel → internal energy ↑, temperature ↑ → adiabatic heating

Vertical temperature changes are largely governed by expansion/compression, not by direct heating.

# Atmospheric Application of the First Law

The First Law: $\boxed{dU = \delta Q - pdV}$ and $\delta Q = 0$ (the process is adiabatic, no heat exchange)

Leads to the adiabatic lapse rate:

$$\boxed{\frac{dT}{dz} = -\frac{g}{c_p}}$$

where $g$ is gravity and $c_p$ is specific heat capacity at constant pressure.

# In-Class Activity

Deriving the Convective Instability

# Pressure-Temperature (P-T) Profiles

| | Earth | Jupiter |
|---|---|---|
| **Troposphere** | Heated from below by sunlight | Heated from below by internal heat |
| **Stratosphere** | Heated from above by ozone (UV) | Heated from above by $CH_4$ + photochemical hazes (UV/IR) |