



· Determine temperature, density changes as a function of

atmosphere (affects dynamics, thermal environment etc.)

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Predict atmospheric environment on other planetary

bodies using point measurements and knowledge of

· Determine mean free path for objects in upper

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Macroscopic state parameters Parameters that describe the general state of an atmosphere					
Parameter S	Symbol	Gas kinetic meaning	Height		Unit
			0 km	300 km	
Chemical composition		ni/n	78% N2 21% O2 1% Ar	78% O 21% N2 1% O2	
Mass density	ρ	Σi mi ni	1.3	2•10-11	kg/m ³
Flow velocity	≯ u	→ < v >	0 – 50	0 - 1000	m/s
Temperature	т	² / ₃ k• ¹ / ₂ mc ²	200 – 320 2500	600 -	к
Pressure	p	⅓nmc ²	105	10 ⁻⁵	Ра
		1 Pa = 1 pasca 1 atm = 10132	I= 1 N/m ² 5 Pa= 760 torr		RK RSITE

Why?

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altitude

molecular interactions

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Gas kinetics Atomic parameters Macroscopic state parameters are sufficient to describe the Particles to consider: . general macroscopic characteristics of an atmosphere. - H He O Ar N2 O2 Particle radius - Not radically different for any of the constituent particles Gas kinetics are necessary to give physical interpretation of the - $1 - 3x10^{-10}$ m (If the particle radius would be scaled up to 1 cm, then macroscopic state parameters. 1m would have to be scaled up to the distance from here to the moon.) Mass number (atomic mass number - sum of protons and neutrons -Gas kinetics are necessary to describe other parameters like vs. Atomic number – number of protons only) – and particle mass (mass number times mass of 1 amu - 1.66×10^{-27} kg) diffusion, viscosity and heat conduction. Degrees of freedom 3 for atoms, usually 5 for molecules: Gas kinetics describe the behaviour of gas particles with atomic rotation about the axis joining the two atoms has no impact on kinetic energy – negligible moment of inertia about this axis. parameters, dynamical variables and boundary conditions. Vibration in the joining axis generally negligible as well

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Gas kinetic parameters At 0 km, assume 300 K, use primary composition N₂ At 1000 km, assume 1000 K, use primary composition O Particle density · Random velocity • Collision frequency Mean free path

Important gas kinetic parameters can be derived if statistical behaviour of gas particles is known Parameter Symbol Height Unit 0 km (300 K, N₂) 300 km (T∞= 1000 K; O) 2x10²⁵ Particle density n 1x10¹⁵ 1/m³ Random velocity Mean random speed m/s 470 1100 6x10⁹ 0.4 1/s Collision frequency 8x10⁻⁸ 3000 Mean free path m YORK * For T=0 C, n=2.69 x 10²⁵ m⁻³

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To repeat:



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Now we want to consider a mix of two gases with particles 1 and particles 2 and temperature 1 and temperature 2. We have then the two Maxwell-Boltzmann speed distributions:

$$f(c_1) = \left(\frac{m_1}{2\pi k T_1}\right)^{\frac{3}{2}} 4\pi c_1^2 e^{\frac{m_0 c_1^2}{2k T_1}}$$
$$f(c_2) = \left(\frac{m_2}{2\pi k T_2}\right)^{\frac{3}{2}} 4\pi c_2^2 e^{\frac{m_0 c_1^2}{2k T_2}}$$

It can be shown that the mean relative velocity is

$$\overline{c}_{1,2} = 4\pi \left(\frac{m_{1,2}}{2\pi k T_{1,2}}\right)^{\frac{3}{2}} \int c_{1,2}^{2} e^{-\frac{m_{1,2}^{2}}{2k T_{1,2}}} dc_{1,2}$$

$$\overline{c}_{1,2} = \sqrt{\frac{8k}{\pi} \left(\frac{T_{1}}{m_{1}} + \frac{T_{2}}{m_{2}}\right)} = \sqrt{\frac{8k T_{1,2}}{\pi m_{1,2}}}$$

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Gas particle 1 maps out volume π(r₁ + r₂)² times c_{1,2} = ⟨|c₁ - c₂|⟩ times Δt. During time interval Δt it will collide with that volume times n₂ particles of particle 2.
 The collision frequency, ν_{1,2}, that is the number of collisions per unit time, Δt, is:
 ν_{1,2} = π(r₁ + r₂)² n₂c_{1,2} / (r₁ = σ_{1,2}n₂c_{1,2})

where $\sigma_{1,2}$ is the collision cross-section. But we still need an explicit number for the collision frequency in terms of temperature of each of the gases and the mass of the particles in each of the two gases.





Parameter	Symbol	Gas kinetic meaning	Height		Unit
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Flow velocity	→ u	→ < v >	0 – 50	0 - 1000	m/s
Temperature	Т	²⁄₃k• 1⁄₂mc²	200 – 320 2500	600 -	К
Pressure	р	⅓nmc ²	105	10-5	Pa













Now to pressure

- Particles (atoms or molecules) of a gas inside the balloon move around randomly.
- During this motion they frequently collide with the each other and with the skin of the balloon.
- The result is a force exerted on the inside of the skin of the balloon.Pressure is the force per surface area.
- This inside gas pressure, P_B, is balanced by the gas pressure, P_A, exerted on the outside of the skin of the balloon, pr instance, the atmosphere.





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Example 2-4



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Specific heat capacity

 $\Delta T = \frac{2}{k} \Delta \overline{U}_f = \frac{2}{k} \frac{\Delta Q}{Nf} = \frac{2\Delta Q}{k \left(\frac{M}{m}\right) f}$

 $\Delta Q(=\Delta U) = \frac{M}{m}f\frac{k}{2}\Delta T$

· Temperature is a measure of a body's heat content. To raise the

Consider a gas of mass M in a fixed enclosure. How much heat

(energy), ΔQ , is needed to raise the temperature of N particles with f degrees of freedom by ΔT ?

Gas heat capacity at constant volume $\Delta Q'(=\Delta U') = \frac{\Delta Q}{M} = c_v \Delta T$ Specific heat needed to raise temperature by ΔT with V=const

Pressure force, Fp

 $\Delta V = A \Delta z$ Piston motion

Heat input

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temperature of a body, heat must be supplied.





at is indeed approximately the atmospheric pressure



 $\Delta W = -F_p \Delta z = -p \Delta V$

Negative sign: energy is lost to the ga





Atmospheric divisions • Temperature · Composition Vertical transport Gravitational binding Thermal plasma

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Atmospheric divisions					
		Inter-	planetary	space	
100,000 km		H-sphere	Effusosphere	Exosphere	
10,000	Thermosphere	Hetero-			Plasma sphere
1000		sphere	Diffusosphere Turbosphere	Barosphere	F-region
100	Mesosphere	Homosphere			D-region
10	Stratosphere				
0	Troposphere				
Quantity	т	Composition	Vertical transport	Grav. binding	Thermal plasma

















Aerostatics As opposed to aerodynamics, aerostatics deals with density allocation at a macroscopic level, e.g. air density variation within the atmosphere as a function of height. It is assumed that the gases are not in motion with respect to the coordinate system they are considered within. That leads us to the aerostatic equation.

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 $\frac{dn}{dz} = -n(h_0)T(h_0)T(z)^{-2}\frac{dT}{dz}e^{-(z-h_0)/H} - n(h_0)\frac{T(h_0)}{T(z)}\frac{1}{H}e^{-(z-h_0)/H}$ $\frac{dn}{dz}\frac{1}{n} = \frac{1}{T}\frac{dT}{dh} + \frac{1}{H} = \frac{1}{H_n}$

The pressure and density scale heights are not the The pressure and density scale magnetic set V_{ORK} same. But since particularly for heights > 200 km V_{ORK}

· Derivation for pundits:

 $\ln \frac{n(h)}{n(h_0)} = -\int_{h_0}^{h} \frac{dz}{H_n(z)}$

 $\frac{dn}{n} = \frac{dz}{H_n}$

 $H_n = \left(\left| \frac{dn}{dz} \right| \frac{1}{n} \right)^{-1}$

Looking at the pressure law we have

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$$n(h) = n_{h_0} \frac{T(h_0)}{T(h)} e^{-(h-h_0)/H}$$

- · We want the change in density over a height change of 100 km
- We need to determine the scale height H for the Mars atmosphere in this region

$$H(z) = \frac{kT(z)}{\overline{m}(z)g(z)}$$



Atmospheric divisions					
		Inter-	planetary	space	
100,000 km 10,000 1000	Thermosphere	H-sphere Hetero- sphere	Effusosphere Diffusosphere Turbosphere	Exosphere	Plasma sphere F-region E-region
10	Stratosphere	nomosphere			D-region
Quantity	T	Composition	Vertical transport	Grav. binding	Thermal plasma

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Vertical transport

- The turbosphere, 0 to 100 km, is the region where convection effectively mixes atmospheric constituents.
- Above the turbosphere lies the diffusosphere, where diffusion is more important than turbulent mixing in distributing the constituents.
- Finally there is the effusosphere, where the atmosphere is no longer well bound to Earth and can escape under the right conditions





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Composition

- The homosphere lies between the Earth's surface and the heterosphere. Gases are nearly uniformly mixed through this layer even though density decreases with height above the surface. The only exceptions is the "ozone layer" from 19 to 50 km and near surface variations in water vapor, carbon dioxide and air pollutants.
 The heterosphere is the outer-most sphere where gases are distributed in distinct layers by gravity according to their atomic weight. Extending from an altitude of 80-100 km, the lightest elements (hydrogen and helium) are found at the outer margins of the atmosphere. The heavier elements (nitrogen and oxygen) are found at the base of the layer.
- The barometric law applies whether we are in an atmosphere composed of a single gas, a well-mixed homosphere or a gravitationally-separated heterosphere

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Gravitational binding The barosphere is the region of the atmosphere which is well bound to the Earth through gravitational attraction. The exosphere starts at about 600 km, where particle concentration is about 10⁷ cm³, to 5000 km, where the concentration is 10² cm³. The exosphere is the outer limit of the Earth's neutral atmosphere. In this region a particle travelling away from the Earth averages only one collision and pursues essentially a ballistic trajectory in the Earth's gravitational field. Particles with sufficient velocity and no electrical charge can escape from the atmosphere.

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Heterosphere

What do we know about the heterosphere?

What do we know about the heterosphere?
Above the homosphere
Starts around 80-100 km
Chemical composition no longer uniform – more dense constituents lower in heterosphere than less dense ones
Leads to the Hydrogensphere (Geocorona)











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Heterospheric density distributions • The barometric law, as we derived it, can only be explicitly evaluated properly for a single gas or a well-mixed gas as in the homosphere where the mean particle mass, $\overline{m}(h)$ is known.

- In the heterosphere $\overline{m}(h)$ is not easily known, since it depends on the density profiles (density as a function of height) of the individual gases. For instance, the gases, O, O₂ and N₂ have different density profiles, and therefore the mean particle mass changes with height.
- If all the gases, i, are in thermodynamic equilibrium, we can use the Dalton-Stefan Law: the total pressure of a gas mixture is the sum of the partial pressures.

$$\sum_{i} p_{i} = \sum_{i} n_{i} kT = nkT = p$$

Substituting into the aerostatic equation





• The combination yields $v_1^* = v_1 \frac{m_1 - m_2}{m_1 + m_2}$ • The change in momentum of particle of type 1 gas is then $\Delta I_1 = (v_1^* - v_1)m_1 = v_1m_1 \left(\frac{m_1 - m_2}{m_1 + m_2} - 1\right) = v_1 \left(\frac{-2m_1m_2}{m_1 + m_2}\right)$ $v_1 = u_1 - u_2$ with $v_1 = u_1 - u_2$ as the difference of the average flow velocities.





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• For the mean change of momentum we have to integrate over the possible impact parameters





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The frictional force that a particle of gas type 1 experiences due to collision with a particle of gas type 2 is then
 F_{fr.1} = ΔI₁(b = 0)/2 v_{1.2}
 For an ensemble of particles of type 1 gas the frictional force per unit volume is



- Frictional force is proportional to flow velocity differences.
- For stationary gases, $\vec{F}_{i,j} = \vec{F}_{fr,1} = 0$.
- For stationary gases each gas behaves as if it were alone in the mix.
- For stationary gases in a mixture the aerostatic equation for a single gas is the same as that for the gas mixture.
- · We can then really write:





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Why? A good knowledge of temperature, total density, concentrations of maior and minor constituents and pressure is important for a wide range of scientific purposes and for the planning and execution of many space missions exploiting the low-earth orbit (LEO) regime below ~ 2500 km altitude. Aerodynamic forces on the spacecraft due to orbital motion of a satellite through a rarefied gas which itself can have variable high velocity winds, are important for planning satellite lifetime, maintenance of orbits, collision avoidance maneuvering and debris monitoring, sizing the necessary propulsion system, design of attitude control system, and estimating the peak accelerations and torques

- Surface corrosion effects due to the impact of large fluxes of atomic oxygen are assessed to predict the degradation of a wide range of
- oxygen are assessed to predict the degradation of a wide range of sensitive coatings of spacecraft and instruments.
- The <u>reactions of atomic oxygen around a spacecraft can also lead to</u> intense "vehicle glow."
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Density variat	tions at 400 ł	¢m	
Туре	Relative change (%)	Frequency (once per)	
Diurnal effects	250	1 day	
Significant Geomagnetic storm	800	3 days	
Solar UV	250	27 days	
Semi annual	120	12 months	
Solar cycle	1600	11 years	
cmc.gsfc.nasa.gov/RoR_WW	N/SWREDI/2015/SatDrag_YZher	ug_060415.pdf $\sum_{\substack{U,N+V\\U,N+V}}$	DRK





























- · Simple model with reasonable results.
- Errors are < 40% during mean solar activities and <60% during max. solar activities.
- Values change only with location:
- $\rho = \rho_0 e^{\frac{h_0 h}{H}}$ - Height: hydrostatic equilibrium + perfect gas - Latitude: change of height because flattening of Earth toward poles.
- Height over ellipsoid changes with longitude

$$\Delta h_{ell} = 0 - 21 \text{ km} \Leftrightarrow \Delta \rho$$

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• Reference density, ρ₀, and reference height, h₀.

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• Scale height, H.



















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Escape time

- How long does it take to completely remove the gas constituents from the atmosphere?
- $b_{\rm esc}$ may be a small portion of 1, but over time some of the light gas constituents, like H, may be lost completely.
- This "escape time" can be computed by considering an escape flux through an area parallel to the exopause.
 Particles moving through this area outward from all
- possible directions have to be considered.
 An integration over the angles φ, θ over a hemisphere
- An integration over the angles φ, θ over a hemisphere needs to be done.
- As a result we get the escape parameter, X, an important parameter for the atmospheres of planets and moons.
- The larger X, the smaller the escape flux. For Jupiter, X~1400. For Mercury, X~2.



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