

Physics 2028: Great Ideas in Science II: The Changing Earth Module Notes

Dr. Donald G. Luttermoser
East Tennessee State University

Edition 2.0

Abstract

These class notes are designed for use of the instructor and students of the course **Physics 2028: Great Ideas in Science II**. This edition was last modified for the Spring 2009 semester.

III. The Changing Earth Atmosphere

A. The Current Earth's Atmosphere

1. Composition of the Atmosphere.

- a) The Earth's atmosphere is simply called **air**. It is primarily composed of many discrete gases, each with its own physical properties, in which varying quantities of tiny solid and liquid particles are suspended.
- b) The composition of the air is not constant; it varies from time to time and from place to place.
 - i) However, if the suspended particles, water vapor, and other variable traces gases were removed from the atmosphere, its makeup is very stable over all of the Earth up to an altitude of about 80 km.
 - ii) As can be seen by Table III-1, two elements, nitrogen and oxygen (in molecular form), make up 99% of the volume of clean, dry air.
 - iii) Most of the remaining 1% is the inert element argon.
 - iv) The carbon dioxide abundance has been increasing since the dawn of the industrial age.
 - v) Water vapor is one of the most variable gases in the atmosphere. In the warm and wet tropics, it may account for up to 4% of the atmosphere by volume, while in the air of deserts and polar regions, it may compromise only a tiny fraction of 1%.

Table III-1: Principal Gases of Dry Air

<i>Symbol</i>	<i>Constituent</i>	<i>Percent by Volume</i>
N ₂	Nitrogen	78.084
O ₂	Oxygen	20.946
A	Argon	0.934
CO ₂	Carbon Dioxide	0.0325
Ne	Neon	0.00182
He	Helium	0.000524
CH ₄	Methane	0.00015
Kr	Krypton	0.000114
H ₂	Hydrogen	0.00005

- c) Also, water is the only substance in the atmosphere that can exist in all three states: *gas*, *liquid*, and *solid*. It is the source of all clouds in the atmosphere and for precipitation.

2. Four distinct layers of the atmosphere exist:

- a) **Troposphere** (weather sphere): Temperature decreases with height due to a density, hence heat capacity, decrease.

i) **Heat capacity** is a measure of the ability of a material to absorb heat.

ii) It is defined as the constant of proportionality between the amount of heat and the change in temperature that the heat produces in the material.

iii) $C = \text{heat capacity} = \frac{\text{change in heat energy}}{\text{change in temperature}}$.

iv) The word troposphere is based on a Greek word meaning *to change*.

- v) The troposphere is the lowest layer of the atmosphere; it begins at the surface and extends to between 7 km (23,000 ft) at the poles and 17 km (56,000 ft) at the equator, with some variation due to weather factors.
 - vi) The troposphere has a great deal of vertical mixing due to solar heating. This heating makes air masses less dense so they rise. When an air mass rises, the pressure upon it decreases so it expands, doing work against the opposing pressure of the surrounding air.
 - vii) As the temperature decreases with height, water vapor in the air mass may condense or solidify, releasing latent heat that further uplifts the air mass. This process determines the maximum rate of decline of temperature with height, called the **adiabatic lapse rate**.
 - viii) The troposphere contains roughly 80% of the total mass of the atmosphere. Fifty percent of the total mass of the atmosphere is located in the lower 5.6 km (18,000 ft) of the troposphere.
- b) **Stratosphere:** Temperature increases with height due to ozone (O₃) absorption of solar UV light.
- i) The boundary between the stratosphere and troposphere is called the **tropopause**.
 - ii) The origin of this word is from the Latin word “stratus” meaning *spreading out*.

- iii) The stratosphere extends from the troposphere's 7–17 km (4.3–11 mi; 23,000–56,000 ft) range to about 51 km (32 mi; 170,000 ft).
 - iv) The stratosphere contains the ozone layer, the part of the Earth's atmosphere which contains relatively high concentrations of ozone. “Relatively high” means a few parts per million \implies much higher than the concentrations in the lower atmosphere but still small compared to the main components of the atmosphere.
 - v) The ozone layer is mainly located in the lower portion of the stratosphere from approximately 15–35 km (9.3–22 mi; 49,000–110,000 ft) above Earth's surface, though the thickness varies seasonally and geographically.
- c) **Mesosphere:** Temperature decreases again due to a sharp decrease in air density and heat capacity.
- i) The boundary between the mesosphere and the stratosphere is called the **stratopause**. It lies typically 50–55 km (31–34 mi; 160,000–180,000 ft) above the ground. The pressure here is 1/1000th sea level.
 - ii) The origin of this word is from a Greek word meaning *middle*.
 - iii) The mesosphere extends from about 50 km (31 mi; 160,000 ft) to the range of 80–85 km (50–53 mi; 260,000–280,000 ft).

- iv) Temperature decreases with height, reaching -100°C (-148.0°F ; 173.1 K) in the upper mesosphere.
 - v) This layer is also where most meteors burn up when entering the atmosphere.
- d) **Thermosphere:** Sharp increase in temperature due to X-rays from the Sun being absorbed by nitrogen and oxygen.
- i) The temperature minimum at the boundary between the thermosphere and the mesosphere is called the **mesopause**. It is the coldest place on Earth, with a temperature of -100°C (-148.0°F ; 173.1 K).
 - ii) X-rays cause these 2 atoms/molecules to ionize.
 - iii) From 80–85 km (50–53 mi; 260,000–280,000 ft) to over 640 km (400 mi; 2,100,000 ft), temperature increasing with height. Although temperatures are high ($T > 1000^{\circ}\text{C}$), air density is very low so total heat content is low.
 - iv) The *International Space Station* orbits in this layer, between 320 and 380 km (200 and 240 mi).
 - v) Higher levels called the **ionosphere** \implies atoms completely ionized. The **aurorae** are located in the ionosphere. The ionosphere marks the inner edge of the **magnetosphere** where charged particles trapped from the **solar wind** are located.

3. Retention of atmospheric gases.

- a) The ability of a planet to hold onto gases in a planetary atmosphere depends upon two competing processes: the planet's gravitational field and the temperature of the planet's atmosphere.
- b) For an object to just overcome any gravitating body's (like the Earth's) potential field, an object has to be launched with **zero** total energy, that is, $|\text{KE}| = |\text{PE}|$ to escape the primary body's (*e.g.*, Earth's) gravitational field \implies the **escape velocity**.
- i) Hence, to calculate the escape velocity from the surface of a large body of mass M and radius R , we just have to set the initial kinetic and potential energy sum to zero and solve for the velocity:

$$E_{\text{tot}} = \frac{1}{2}mv_{\text{esc}}^2 - \frac{GMm}{R} = 0 . \quad (\text{III-1})$$

- ii) This gives the equation for the **escape velocity** (or escape speed):

$$\boxed{v_{\text{esc}} = \sqrt{\frac{2GM}{R}}} . \quad (\text{III-2})$$

- iii) As can be seen from Eq. (III-2), the escape velocity does not depend upon the mass of the escaping body (or particle). Using the values for Earth in Eq. (III-2), we get

$$v_{\text{esc}} = \sqrt{\frac{2GM_{\oplus}}{R_{\oplus}}} , \quad (\text{III-3})$$

or $v_{\text{esc}} = 11.2$ km/s to leave the Earth's gravitational field.

- iv) For an object to escape the gravitational field of a primary body, it must achieve a velocity greater than or equal to the escape velocity: $v \geq v_{\text{esc}}$.
- c) The **kinetic theory of gases** describes the microscopic motion of gas particles. It assumes that the gas behaves *ideally* (*i.e.*, their equation of state obeys the **ideal gas law**).
- d) At the heart of this theory: **The temperature of the gas is related to the average velocity of a gas particle.**
- i) Thermal energy = average kinetic energy of particles in the gas:

$$\mathbf{TE} = \overline{\mathbf{KE}}$$

or

$$\boxed{\frac{3}{2}k_{\text{B}}T = \frac{1}{2}m\overline{v^2}} \quad (\text{III-4})$$

where the ‘overline’ indicates *average*.

- ii) The average velocity of a gas particle is

$$\overline{v^2} = \overline{v_x^2} + \overline{v_y^2} + \overline{v_z^2} . \quad (\text{III-5})$$

- The average component velocities are equal to each other for random motion:

$$\overline{v_x^2} = \overline{v_y^2} = \overline{v_z^2} .$$

- So, Eq. (III-5) can be rewritten as

$$\overline{v^2} = 3\overline{v_x^2} . \quad (\text{III-6})$$

- e) A **degree of freedom** in a gas refers to the number of independent means by which a gas particle can possess energy.

- If it moves in the x , y , and z directions, it has 3 degrees of freedom.
- So, we can write three separate energy equations:

$$\begin{aligned}
 E_x &= \frac{1}{2}m\overline{v_x^2} = \frac{1}{2}k_B T \\
 E_y &= \frac{1}{2}m\overline{v_y^2} = \frac{1}{2}k_B T \\
 E_z &= \frac{1}{2}m\overline{v_z^2} = \frac{1}{2}k_B T
 \end{aligned}$$

and the average kinetic energy is then the sum of the energies in these three different directions:

$$\begin{aligned}
 E &= E_x + E_y + E_z = \frac{1}{2}m(\overline{v_x^2} + \overline{v_y^2} + \overline{v_z^2}) \\
 &= \frac{1}{2}m(\overline{v^2}) = \frac{1}{2}k_B T + \frac{1}{2}k_B T + \frac{1}{2}k_B T \\
 &= \frac{3}{2}k_B T ,
 \end{aligned}$$

or

$$\overline{v^2} = \frac{3k_B T}{m} . \tag{III-7}$$

- f) The square root of $\overline{v^2}$ is called the **root-mean-square** (rms) velocity:

$$v_{\text{rms}} \equiv \sqrt{\overline{v^2}} = \sqrt{\frac{3k_B T}{m}} \tag{III-8}$$

\implies when we talk about velocity of gas particles, we will always mean v_{rms} . In this equation, k_B is Boltzmann's constant, T is temperature measured in Kelvin, and m is the mass of a given gas particle. As can be seen by this equation, the lower the mass of a gas particle the higher the thermal velocity of the particle.

- g) The temperature of a planetary depends upon a variety of factors, including the amount of greenhouse gases (see

below) contained in the atmosphere. However the most important factor is the distance that a planet is from its star, in our case, the Sun.

- h)** As such, if $v_{\text{rms}} > v_{\text{esc}}$, a planet will gradually lose such a gas over time. This is why the abundance of He and H₂ is so low in the Earth's atmosphere and why the Moon has no atmosphere.

4. Ozone depletion.

- a)** Ozone (O₃) in the stratosphere absorbs solar UV light.
- b)** UV light has higher energy than visible light \implies enough energy to break apart complex molecule chains.
 - i)** UV light can alter the structure of the DNA molecule \implies gives rise to **mutations**.
 - ii)** Most mutations are bad (*i.e.*, harmful) to living organisms \implies cancer results.
- c)** Ozone reacts with hydrofluorocarbons (a common refrigerant):
 - i)** $\text{CH}_3\text{CHF}_2 + \text{O}_3 \rightarrow \text{CO}_2 + \text{H}_2\text{O} + \text{CH}_2\text{F}_2$
(ethylidene fluoride) + (ozone) \rightarrow (carbon dioxide)
+ (water) + (a hydrofluorocarbon radical).
 - ii)** The ozone disappears! The resulting molecules have no absorption lines in the UV \rightarrow the solar UV radiation is able to reach the ground.

5. The Greenhouse Effect.

- a) How a greenhouse works.
 - i) Visible light from the Sun is able to pass through the glass of a greenhouse and heats the inside of the greenhouse.
 - ii) The insides warms to a temperature which emits IR light \implies radiates like a blackbody.
 - iii) The glass is *opaque* to IR light \implies the IR photons cannot escape into the outside environment — the greenhouse heats up!
- b) CO₂ and H₂O gas in the Earth's atmosphere works the same way as the glass in a greenhouse.
 - i) Solar visible light passes through the atmosphere unimpeded.
 - ii) Heats the ground so that it radiates IR light.
 - iii) IR light then radiates outward back into space, however, the CO₂ and H₂O absorb this light which heats the atmosphere.
- c) If it wasn't for CO₂ and H₂O, the Earth's atmosphere (and surface) would be too cold for liquid water to exist early in the history of the planet \implies life would not have formed or evolved.
- d) The burning of fossil fuels releases tremendous amounts of gaseous CO₂ into the atmosphere.
 - i) CO₂ abundance has increased by over 20% over the past 100 years due to the industrial revolution.

- ii) The average temperature of the Earth also has increased (by about $3 \text{ K} = 3^\circ\text{C}$) over this same time period.
- iii) The hypothesis has been made that the increased CO_2 abundance has caused this temperature increase.
- e) Venus has experienced a **runaway greenhouse effect**.
- f) We will have further details of the greenhouse effect in the atmospheric modeling section later in this section of the notes.

B. Atmospheric Modeling

1. There are two main conditions which dictate how the atmosphere of a planet is structured and how it evolves over time.

a) The first is the *size and mass of the planet* which determines the escape velocity v_{esc} from the planet via

$$v_{\text{esc}} = \sqrt{\frac{2GM_p}{R_p}}, \quad (\text{III-9})$$

where M_p is the mass of the planet, R_p is the radius of the planet, and G is Newton's universal constant of gravity.

b) The second is the *stellar energy input* which is a function of the distance the planet is from the star (r_p) and the luminosity of the star (L_\star).

i) If blackbody radiation is assumed, the stellar luminosity is a function of temperature (T_\star) and radius (R_\star).

ii) These stellar parameters determine the surface temperature of the planetary atmosphere T_p (in

conjunction with the albedo A of the planet/atmosphere) via

$$T_p = (1 - A)^{1/4} \sqrt{\frac{R_\star}{2r_p}} T_\star . \quad (\text{III-10})$$

iii) Initially in modeling, it is assumed that the fraction of energy that is not reflected back into space is completely absorbed and not scattered (*i.e.*, thermal equilibrium). However once initial models are converged, scattering is included in the calculations.

iv) Heat retention due to the greenhouse effect also needs to be included.

2. Assumptions used in atmospheric modeling.

- a) Geometry of the atmosphere: typically either the assumptions of *plane parallel* or *spherically symmetric* are used.
- b) Transport of energy: usually only *radiation transport* and *convective transport* are important.
- c) Equation of state of the gas: usually the *ideal gas law* is assumed.
- d) *Equilibrium vs. non-equilibrium chemistry*: initial models usually assume equilibrium conditions exist in an atmosphere and once these models are converged, non-equilibrium equations are used. These calculations also need to include dust formation.
- e) *Local thermodynamic equilibrium (LTE) vs. non-local thermodynamic equilibrium (NLTE) radiation transport*: once again, initial models assume LTE then NLTE equations are brought into the calculations.

- f) *Opacities*: Bound-bound, bound-free, and free-free transitions for atoms and molecules are needed; electron scattering is needed for ionospheres; Rayleigh (molecule) and Mie (dust) scattering are needed.
 - g) *Precipitation* and the water cycle are needed for those planets where liquid water can exist (*i.e.*, those planets in a habital (life) zone around a star).
 - h) Finally, *static* vs. *dynamic* atmospheres: the difference between these two is whether winds exist in an atmosphere. Initial models usually assume a static atmosphere where the **hydrostatic equilibrium** is used to determine how pressure changes with height.
3. The physics and chemistry of a planetary atmosphere is driven by the radiation falling upon the atmosphere. As such, stellar evolution must be taken into account when modeling planetary atmospheric structure and evolution.
- a) Ninety percent of the thermonuclear life of a star is spent on the main sequence. The main sequence lifetime is determined via

$$t_{MS} = 1.1 \times 10^{11} f X_H \frac{M_\star/M_\odot}{L_\star/L_\odot} \text{ years} , \quad (\text{III-11})$$
 where f is the fraction of the star's mass involved in nuclear fusion, X_H is the abundance of hydrogen, M_\star is the mass of the star, and M_\odot and L_\odot are the Sun's mass and luminosity, respectively.
 - b) While on the main sequence, the temperature and luminosity of a star will slowly increase over time changing less than 10% during the main sequence lifetime.

- c) The ultraviolet and X-ray flux of solar-like stars primarily arises from chromospheric and coronal regions of a stellar atmosphere. These 2 regions are hotter than the underlying photosphere where the bulk of the energy flux is emitted. This heating primarily arises from magnetic fields on the surface of a star which diminish over time due to the slowing of the rotation of stars due to magnetic braking with the magnetic field of the interstellar medium. As such, the UV and X-ray flux diminishes over the course of a star's main sequence lifetime.
- d) Once the evolutionary time exceeds the main sequence lifetime, it follows evolutionary tracks on the HR Diagram where the star expands and its surface cools \implies it becomes a red giant. The large increase in size causes a large increase in luminosity.

4. The basic modeling technique.

- a) The pressure scale height is determined from the hydrostatic equilibrium (HSE) equation:

$$\frac{dP}{dz} = -g \rho \quad (\text{III-12})$$

for a plane-parallel atmosphere or

$$\frac{dP}{dr} = -\frac{G M \rho}{r^2} \quad (\text{III-13})$$

for a spherically-symmetric atmosphere, where P is the total pressure, z is the height in the atmosphere, g is the surface gravity, ρ is the gas density, and r is the distance from the planet's center, and M is the mass of material in a shell of thickness dr .

- b) In addition to this equation, we also need an equation of state for the gas. As mentioned we use the ideal gas law:

$$PV = nRT \quad (\text{III-14})$$

or

$$P = Nk_{\text{B}}T, \quad (\text{III-15})$$

where V is the volume of gas, n is the number of gas particles in moles, R is the universal gas constant, T is temperature, N is the particle density, and k_{B} is Boltzmann's constant.

- c) The assumption of HSE along with the ideal gas law is used to calculate P , T , and ρ as a function of height (or radius). From this, the thickness τ of the atmosphere is calculated under the condition that $z = \tau$ when $P = 0.001 P_{\circ}$, where P_{\circ} is the surface atmospheric pressure.
- d) With this structure in place the chemical composition is determined by initially assuming chemical equilibrium using the partition functions of atomic and molecular species of importance. The condensation and freezing points of the gases are included, which also will affect the atmospheric gas composition. We will not describe non-equilibrium calculations due to their difficulty.
- e) Once the chemical composition is determined, this data to determine the opacity of the gas as a function of wavelength.
- f) The equations of radiative transfer and convection are then solved.
- i) The mixing-length theory is typically assumed to accurately describes convection.

- ii) Initial atmosphere models assume local thermodynamic equilibrium (LTE) in the solution of the transfer equation. Since the densities in a planetary atmosphere are typically large, the LTE assumption should be valid.
 - iii) Published stellar spectra is typically used as input of the stellar radiation field for the radiative transfer calculations.
 - iv) These calculations will then result in a temperature-density stratification for a given evolutionary time.
- g) As a planet evolves, a modeling code must determine whether conditions are appropriate for life to form. If so, non-equilibrium chemistry must be introduced in the form of life affecting the composition of an atmosphere.
5. The physics of retention of a planetary atmosphere.
- a) A variety of processes are important to the ability of a planet to hang on to an atmosphere.
 - b) The first as stated in the last section depends upon the amount of energy falling onto a planetary atmosphere from the star (or stars) in the system versus the strength of the gravitational field of a given planet. The loss of atmospheric gas from this processes is known as **radiative ablation**.
 - c) Beside this process, a planetary atmosphere can either gain mass or lose mass through momentum exchange, sometimes called **momentum ablation**, with a stellar wind.

- i) This change of the mass of a planetary atmosphere will depend upon the strength of a stellar (or in the case of the Solar System, solar) wind.
- ii) Many cool giant stars have rather massive winds which makes this process important in the distant future of the evolution of the Solar System when the Sun becomes a red giant star.
- iii) For this process we need to define the *accretion radius* of a planet R_{BHL} relative to the planet's size which is given by

$$\frac{R_{\text{BHL}}}{R_{\text{P}}} = \frac{v_{\text{esc}}^2(R_{\text{P}})}{v_{\text{rel}}^2(r)}, \quad (\text{III-16})$$

where v_{rel} is the relative speed between the accreted matter and the planet (in this expression, gas pressure effects are assumed negligible) and R_{P} is the radius of the planet in question. The approach describes how streamline flow is gravitationally focused downstream of the planet. Crossing wind streams lead to a shock, and a some fraction of this gas falls back onto the planet.

- iv) One considers accretion to be important only if $R_{\text{BHL}} > R_{\text{P}}$ (*i.e.*, when the gravitational potential at the planet is “deeper” than the kinetic energy of the incoming matter).
- v) To estimate how much mass is lost by a planet via a stellar wind, it is assumed that the deposition of kinetic energy by the giant star wind goes into heating the outer atmosphere of the planet (in

addition to the radiative heating) and driving off mass.

vi) Energy conservation thus demands the following:

$$\frac{1}{2} \Delta M_{\text{P}} v_{\text{P}}^2 = \frac{1}{2} \Delta M_{*} \frac{\Delta \Omega_{\text{P}}}{4\pi} v_{\text{w}}^2, \quad (\text{III-17})$$

where ΔM_{P} is the total mass lost by the planet, v_{P} is the speed at which it is lost, ΔM_{*} is the total mass lost by the star, $\Delta \Omega_{\text{P}}$ is the fraction of the wind that is intercepted by the planet, and v_{w} is the total speed of the impinging stellar flow. The equation can be re-expressed as fractional mass lost, with

$$\frac{\Delta M_{\text{P}}}{M_{\text{P}}} = \frac{\Delta \Omega_{\text{P}} \Delta M_{*}}{4\pi M_{\text{P}}} \frac{v_{\text{w}}^2}{v_{\text{P}}^2}. \quad (\text{III-18})$$

vii) The curves of Figure 1 closely follow a power-law trend of r^{-2} (the plotted curves are slightly steeper than this), implying that the factor $\Delta \Omega_{\text{P}}$ dominates the variation with radius. This trend results because the wind speed term v_{∞}^2 is considerably larger than either the orbital motion term v_{orb}^2 or the planetary escape speed term v_{esc}^2 .

C. Evolution of the Earth's Atmosphere

1. The early Earth atmosphere.

- a) At the Earth's formation, light elements such as hydrogen and helium exist in large quantities near the Earth's surface.
- b) After loss of the hydrogen, helium and other hydrogen-containing gases from early Earth due to the Sun's radiation, primitive Earth was devoid of an atmosphere.

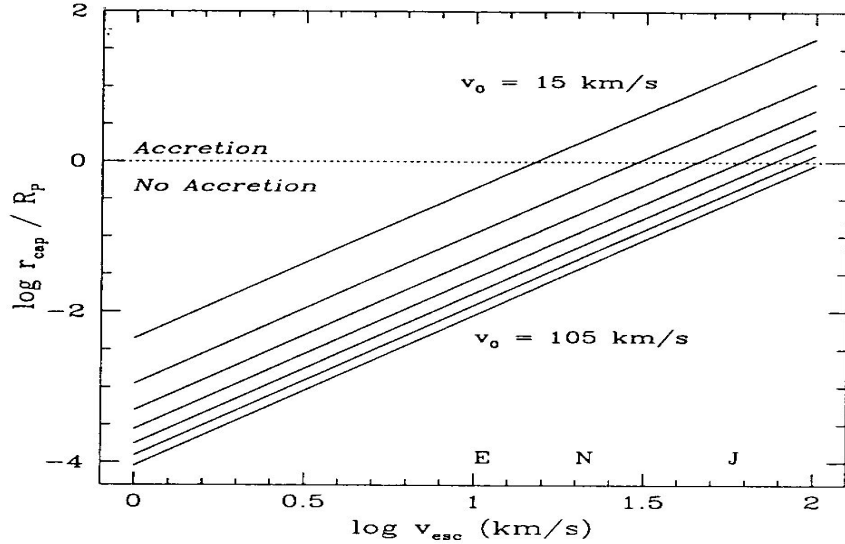


Figure III-1: A plot of the BHL capture radius r_{cap} relative to the planetary radius as a function of planetary escape speed. The solid curves are for different relative velocities of incoming flow v_o from 15 to 105 km/s in intervals of 15 km/s. The condition of BHL accretion requires that r_{cap} exceeds R_p . Note that even if the Earth were motionless, it would still fail to accrete the slowest AGB winds beyond its own geometric cross-section.

- c) The first atmosphere was formed by outgassing of gases trapped in the interior of the early Earth, which still goes on today in volcanoes.
- d) For the Early Earth, extreme volcanism occurred during differentiation, when massive heating and fluid-like motion in the mantle occurred. It is likely that the bulk of the atmosphere was derived from degassing early in the Earth's history. The gases emitted by volcanoes today are in the following table.

**Composition of volcanic gases
for three recent volcanoes**

H ₂ O	CO ₂	SO ₂	H ₂ S	HCl
95	1.1	1.5	0.07	0.006
96	1.9	2.3	0.08	0.004
97	1.1	1.5	0.07	0.006

- e) Life started to have a major impact on the environment once photosynthetic organisms evolved. These organisms, blue-green algae, fed off atmospheric carbon dioxide and converted much of it into marine sediments consisting of the shells of sea creatures.
- f) While photosynthetic life reduced the carbon dioxide content of the atmosphere, it also started to produce oxygen.
 - i) For a long time, the oxygen produced did not build up in the atmosphere, since it was taken up by rocks, as recorded in banded iron formations and continental red beds.
 - ii) To this day, the majority of oxygen produced over time is locked up in the ancient “banded rock” and “red bed” formations.
 - iii) It was not until probably only 1 billion years ago that the reservoirs of oxidizable rock became saturated and the free oxygen stayed in the air.
- g) Once oxygen had been produced, ultraviolet light split the molecules, producing the ozone UV shield as a by-product. Only at this point did life move out of the oceans and respiration evolved.
- h) Oxygen became a key atmospheric constituent due entirely to life processes. It built up slowly over time, first oxidizing materials in the oceans and then on land.
- i) Sometime just before the Cambrian, atmospheric oxygen reached levels close enough to today’s level (20%) to allow for the rapid evolution of the higher life forms. For the rest

of geologic time, the oxygen in the atmosphere has been maintained by the photosynthesis of the green plants of the world, much of it by green algae in the surface waters of the ocean.

2. The distant future of the Solar System and Planetary Atmospheres.

- a) Important questions that need to be asked about the Earth and the other planets in the Solar System (and planets in other stellar systems) when a star nears the end of its thermonuclear life include
 - i) Can Earth-like planets retain an atmosphere at late stellar phases?
 - ii) Will gas giants like Jupiter experience substantial mass loss, or accretion of stellar wind gas?
 - iii) What effect do the strong ultraviolet (UV) emission lines from the thick chromospheres and outward propagating shocks of red giant branch (RGB) and asymptotic giant branch (AGB) stars have on the structure of their planetary companions?
- b) For planets in orbits around red giant stars object like Jupiter can suffer evaporative mass loss due to radiative and momentum ablation of up to about 30% for quite small orbits of 0.3 A.U. above a solar/stellar photosphere, and Saturn-like objects can lose more than 10% of their mass out to modest-sized orbits of order 1 A.U. above the photosphere.

- c) A body like Uranus might evaporate entirely at an orbit of 1 A.U., whereas an Earth-like body will lose its atmosphere at an orbit as large as 5 A.U.
- d) The major conclusion is that atmospheric losses because of red giant winds might be significant, depending primarily on the mass of the planet, the speed of the stellar wind, and the orbital distance of the planet from the star.
- e) Over the course of time, the radius of the planet's orbit will begin to drift: either outward because of mass lost by the star or potentially inward because of drag with the solar wind. Modeling has shown that this first effect dominates the later for the inner planets (at least until the future Sun engulfs them).
- f) If a planet experiences significant mass loss during the late stages of the Sun's evolution, then its escape speed will decrease, and mass loss will become even easier due to radiation and momentum ablation.
 - i) For Jovian planets, their size will change as a result of this mass loss, reducing its wind intercepting cross-section, which will have a compensating effect for the reduced escape speed v_{esc} .
 - ii) For terrestrial planets the solid planet should remain of constant radius throughout the loss of its atmosphere (note that the mass of a terrestrial atmosphere is small fraction of a planet's total mass).