

Radiation

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致谢：本课件中部分资料来自李成才老师
(特别是关于辐射的部分)。



Outline

- Introduction
- Concepts
- Absorption
- Scattering
- Radiative transfer
- Radiative equilibrium temperature
- Radiative heating and cooling

思考题

Consider thermal emission from an isothermal, nonblack cloud. Suppose there is a stratus cloud with stratified atmosphere. The top of the cloud is at $\tau = 0$, and the bottom is at $\tau = \infty$. Assume that we are in the thermal region ($F_{\boxtimes} = 0$), that the cloud is isothermal ($\frac{dB}{d\tau} = 0$), that the scattering is isotropic ($g = 0$), and that the single scattering albedo (ω_0) is a constant. Thus, the radiative transfer of diffuse flux becomes:

$$\frac{d^2F}{d\tau^2} = \alpha^2 F, \quad \alpha^2 = 3(1 - \omega_0)$$

(i) Show that the boundary condition at $\tau = 0$ is:

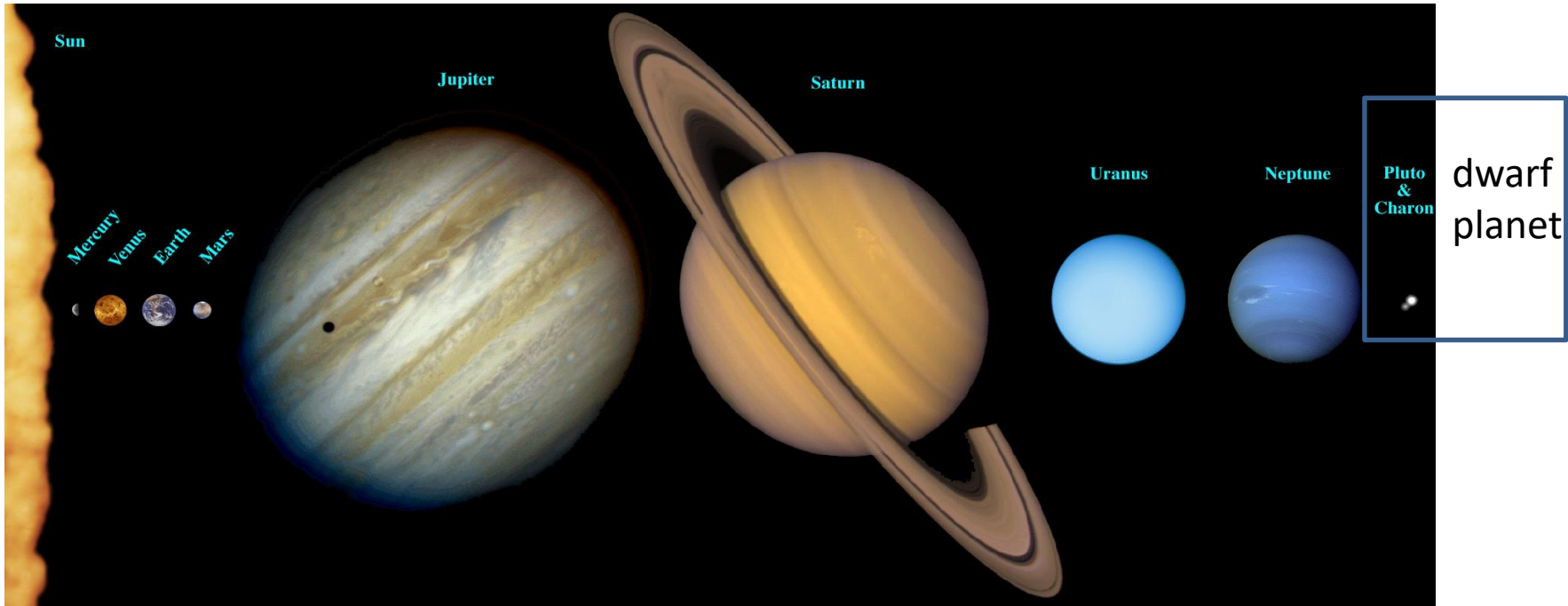
$$\left(\frac{dF}{d\tau}\right)_{\tau=0} = 4\pi(1 - \omega_0) \left(\frac{F(0)}{2\pi} - B\right)$$

Show that:

$$\frac{F(0)}{\pi B} = \frac{4(1 - \omega_0)}{2(1 - \omega_0) + \sqrt{3(1 - \omega_0)}}$$

(ii) The above formulae are approximate. What should be flux be for a black body ($\omega_0 = 0$)? Correct the above formula with a constant factor to allow for this error and calculate $\frac{F(0)}{\pi B}$ for $\omega_0 = 1.0, 0.8, 0.6, 0.4, 0.2, 0.0$.

Planets in the Solar System

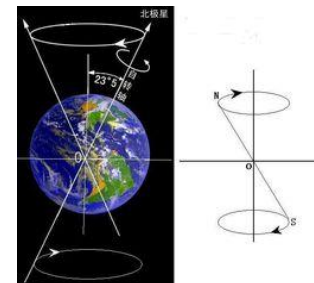
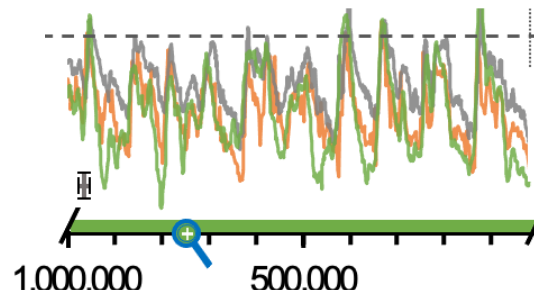


- 太阳活动?
- 地球公转轨道?
- 黄赤交角?
- 岁差?
- 可宜居性?

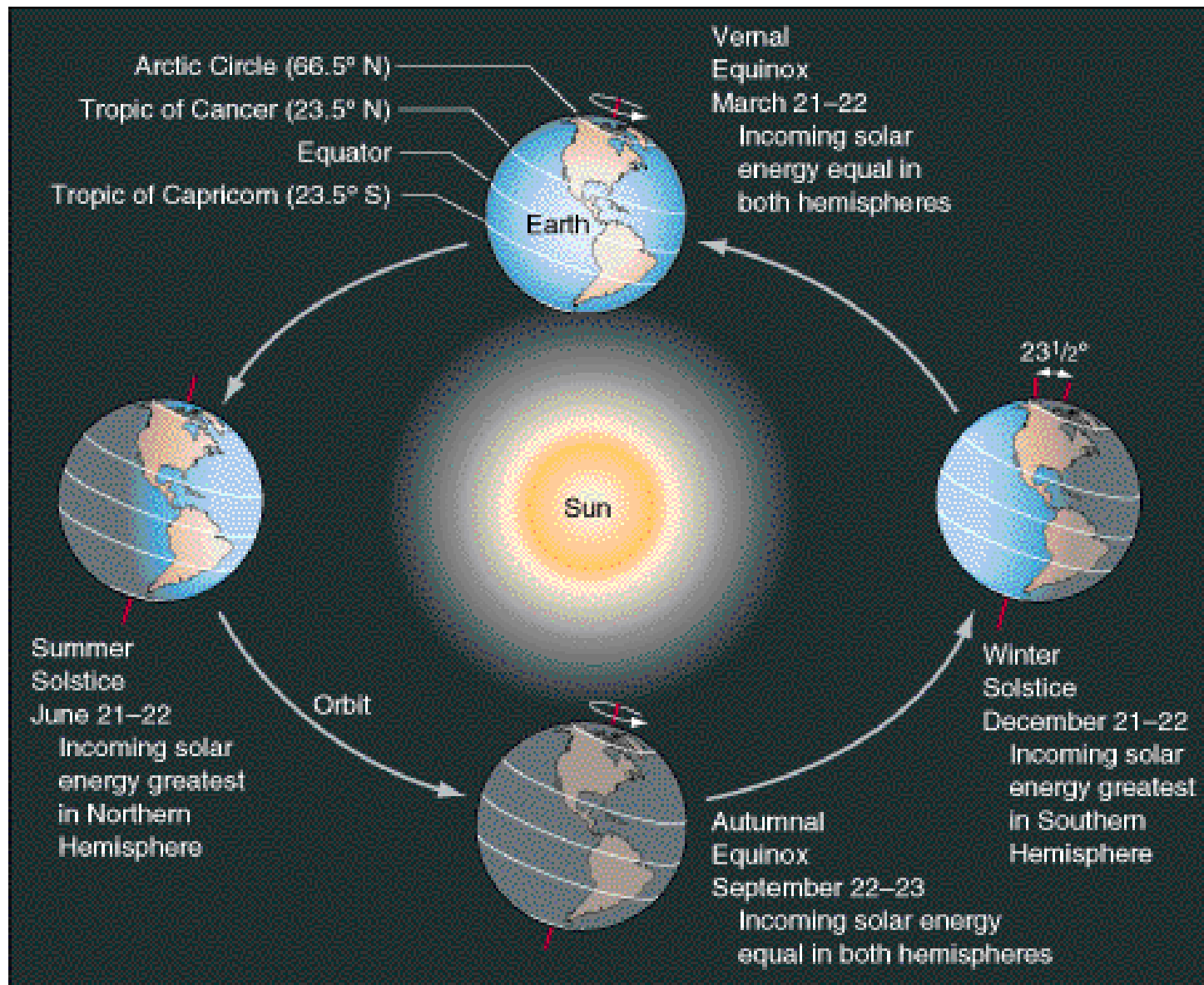
地球基本参数

- 日地距离: 平均 1.496×10^8 km, or 1 AU (range: 0.973–1.017 AU)
- 地球轨道偏心率: 0.0167 (周期: 40万年、10万年)
- 地球自转轴角度: $\sim 23.5^\circ$ (周期: 4.1万年)
- 地球自转轴进动 (岁差; 周期: 2.6万年)
- 地球公转周期: 1年, 自转周期: 1天
- 地球半径: ~ 6371 km (极半径 6357 km, 赤道半径 6378 km)
- 太阳常数: 日地平均距离处的太阳辐射, $1361\text{--}1362 \text{ w/m}^2$
- 地球系统的太阳辐射返照率: $\sim 29\%$, 太阳辐射量净量: $\sim 240 \text{ w/m}^2$

米兰科维奇理论?



Seasons

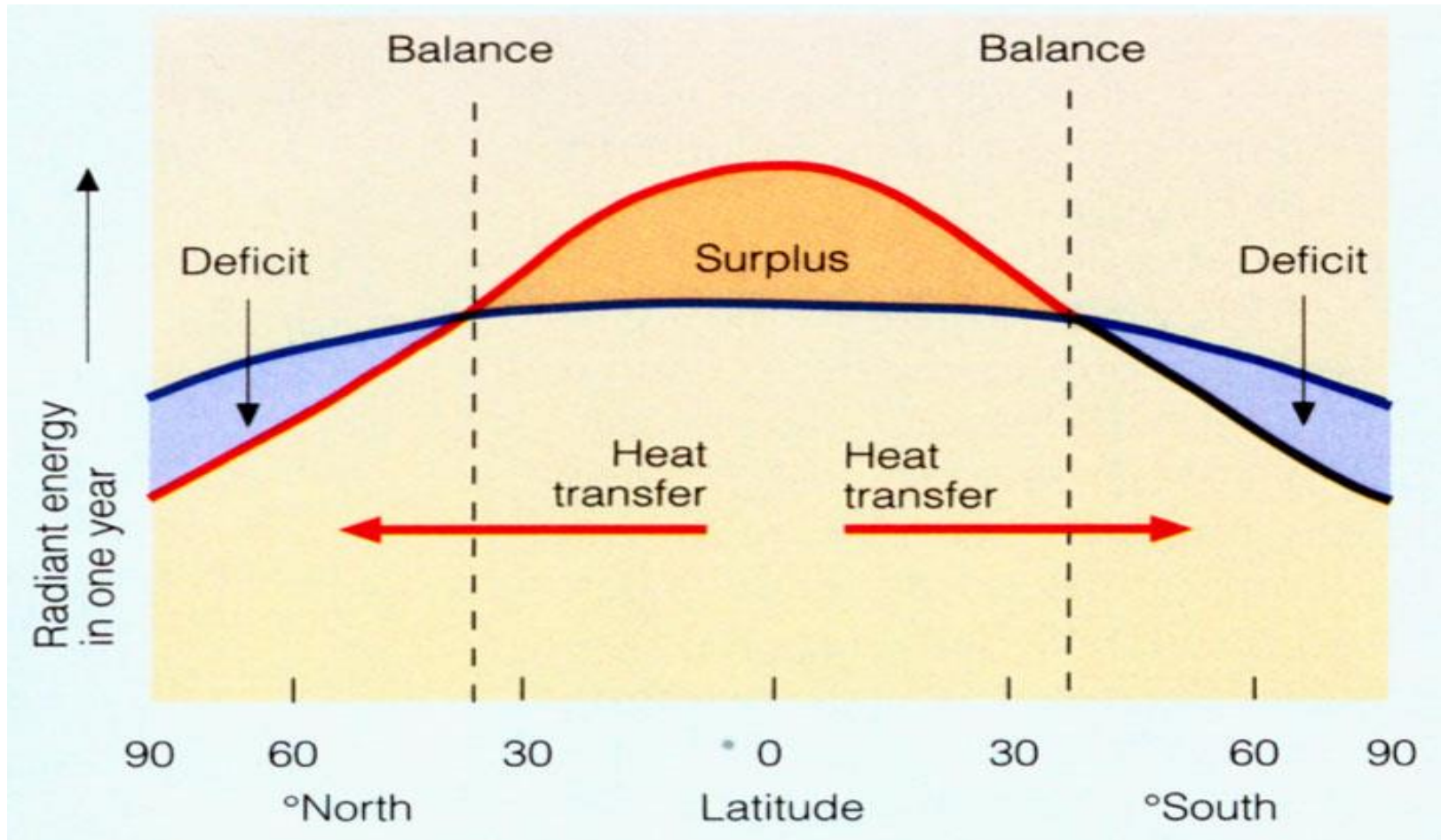


Atmospheric Compositions

Composition of the Atmosphere

Constituent	Chemical formula	Molecular weight (¹² C = 12)	Fraction by volume in dry air	Total mass (g)
Total atmosphere		28.97		5.136×10^{21}
Dry air		28.964	100.0 %	5.119×10^{21}
Nitrogen	N ₂	28.013	78.08 %	3.87×10^{21}
Oxygen	O ₂	31.999	20.95 %	1.185×10^{21}
Argon	Ar	39.948	0.934 %	6.59×10^{19}
Water vapor	H ₂ O	18.015	Variable	1.7×10^{19}
Carbon dioxide	CO ₂	44.01	353 ppmv ^a	$\sim 2.76 \times 10^{18}$
Neon	Ne	20.183	18.18 ppmv	6.48×10^{16}
Krypton	Kr	83.80	1.14 ppmv	1.69×10^{16}
Helium	He	4.003	5.24 ppmv	3.71×10^{15}
Methane	CH ₄	16.043	1.72 ppmv ^a	$\sim 4.9 \times 10^{15}$
Xenon	Xe	131.30	87 ppbv	2.02×10^{15}
Ozone	O ₃	47.998	Variable	$\sim 3.3 \times 10^{15}$
Nitrous oxide	N ₂ O	44.013	310 ppbv ^a	$\sim 2.3 \times 10^{15}$
Carbon monoxide	CO	28.01	120 ppbv	$\sim 5.9 \times 10^{14}$
Hydrogen	H ₂	2.016	500 ppbv	$\sim 1.8 \times 10^{14}$
Ammonia	NH ₃	17.03	100 ppbv	$\sim 3.0 \times 10^{13}$
Nitrogen dioxide	NO ₂	46.00	1 ppbv	$\sim 8.1 \times 10^{12}$
Sulfur dioxide	SO ₂	64.06	200 pptv	$\sim 2.3 \times 10^{12}$
Hydrogen sulfide	H ₂ S	34.08	200 pptv	$\sim 1.2 \times 10^{12}$
CFC-12	CCl ₂ F ₂	120.91	480 pptv ^a	$\sim 1.0 \times 10^{13}$
CFC-11	CCl ₃ F	137.37	280 pptv ^a	$\sim 6.8 \times 10^{12}$

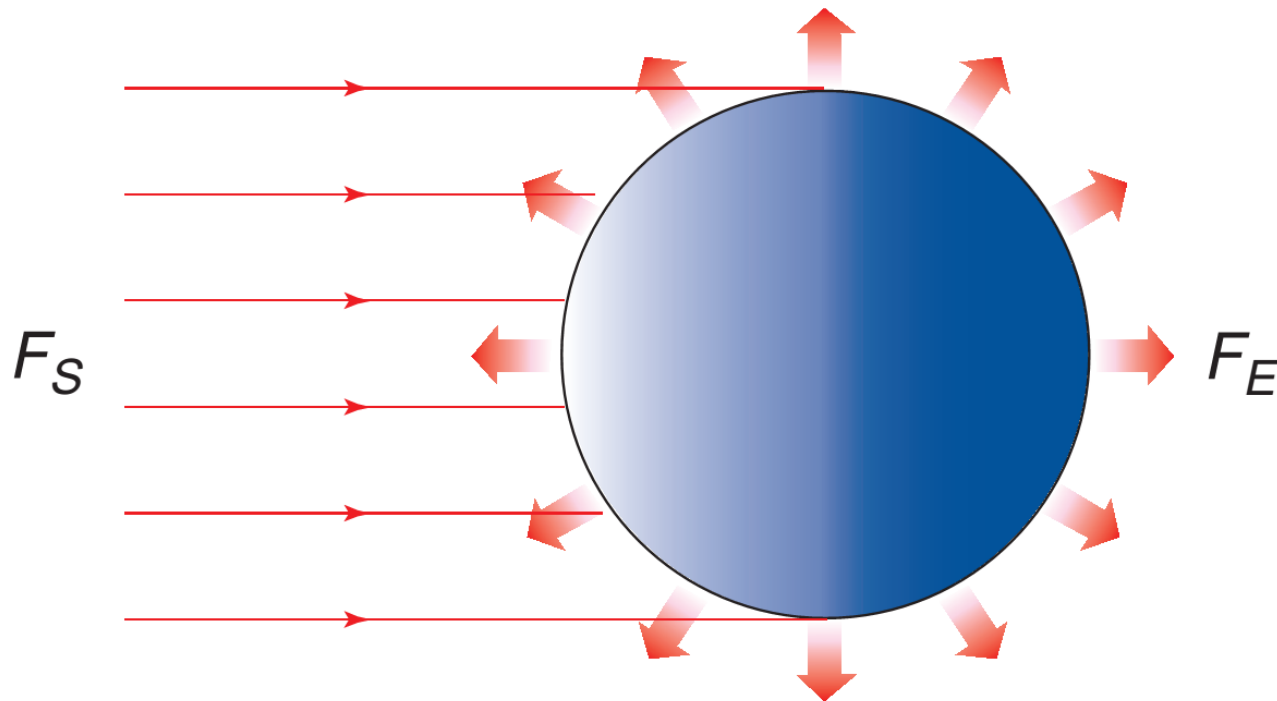
Longwave and Shortwave Radiation Imbalance



地气系统辐射平衡：一箱模型

- 从全球长期平均温度来看，地气系统的温度多年基本不变，所以全球应当是（基本）达到辐射平衡的。
- 可以用一个简单的地气系统辐射平衡模式来估算地气系统的辐射平衡。

$$F_S = F_E \quad (\text{辐射通量})$$



地气系统辐射平衡

- 设地球系统是一个半径为 r 的球，它对太阳短波辐射的反射率（也称行星反照率）为 R 。则其接收的短波辐射通量

$$F_S = S_0 \pi r^2 (1 - R)$$

其中， S_0 为太阳常数

- 地气系统（在长波处）可看作为黑体，其有效温度为 T_e ，它向宇宙空间发射的长波辐射通量

$$F_E = 4\pi r^2 \sigma T_e^4$$

地气系统辐射平衡

- 在地气系统达到辐射平衡时

$$S_0 \pi r^2 (1 - R) = 4\pi r^2 \sigma T_e^4$$

$$T_e = \sqrt[4]{\frac{S_0(1 - R)}{4\sigma}}$$

- 取 $S_0 = 1361 \text{ w m}^{-2}$, $R = 0.29$, 可算出

$$T_e = 255.5 \text{ K} \approx -18^\circ \text{C}$$

T_e 为地气系统能量平衡时的“有效温度”
这比观测到的地表平均温度(288 K)小33 K

太阳系行星气候

行星	离太阳距离 (10^6km)	太阳常数 (w m^{-2})	$A=0.29$ 时的有效温度(K)	实测的行星反照率	实测A时的 T_e (K)
水星	58			0.06	442
金星	108			0.78	227
地球	150	1361		0.3	255
火星	228			0.17	216
木星	778			0.45	106

“大气+地表” 辐射平衡：两箱模型

利用“大气+地表”辐射平衡，计算地面平衡温度：

其中， R 为地气系统对短波辐射的返照率， A_s 为大气短波(净)吸收率， A_l 为大气长波(净)吸收率，地面在长波波段为黑体

$$\frac{S_0}{4} \downarrow \dots \dots \frac{S_0}{4} R \uparrow \dots \dots \sigma T_a^4 A_l \uparrow \dots \dots \sigma T_s^4 (1 - A_l) \uparrow$$



$$\frac{S_0}{4} (1 - R - A_s) \downarrow \dots \dots \sigma T_a^4 A_l \downarrow \dots \dots \sigma T_s^4 \uparrow$$

“大气+地表” 辐射平衡

TOA辐射平衡:
$$\frac{S_0}{4} (1 - R) = \sigma T_a^4 A_l + \sigma T_s^4 (1 - A_l)$$

地表辐射平衡:
$$\frac{S_0}{4} (1 - R - A_s) + \sigma T_a^4 A_l = \sigma T_s^4$$

因此,

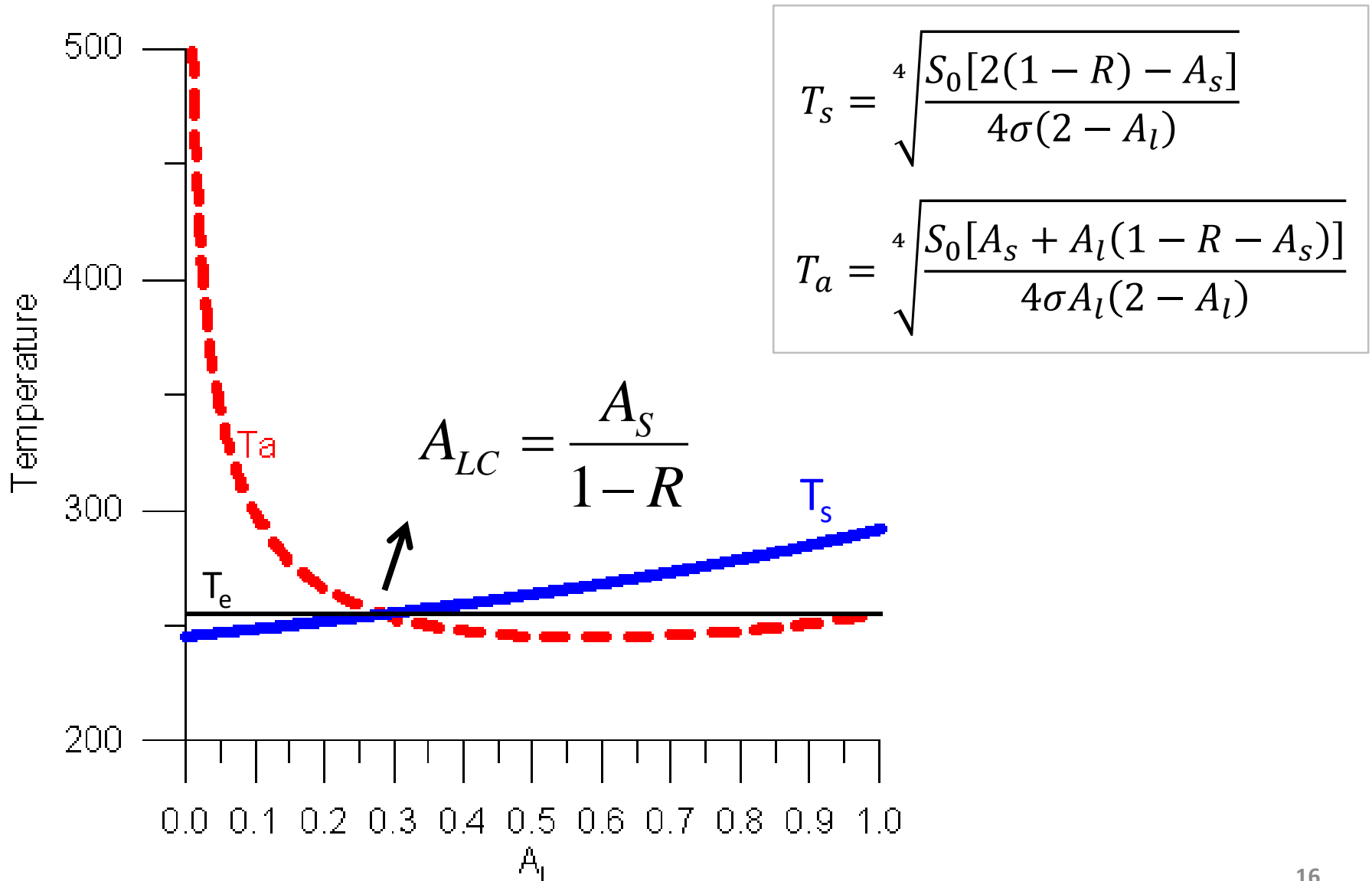
地表温度:
$$T_s = \sqrt[4]{\frac{S_0 [2(1 - R) - A_s]}{4\sigma(2 - A_l)}}$$

大气温度:
$$T_a = \sqrt[4]{\frac{S_0 [A_s + A_l(1 - R - A_s)]}{4\sigma A_l(2 - A_l)}}$$

“大气+地表” 辐射平衡

- 取 $A_l = 0.9$, $A_s = 0.2$, $R = 0.3$, 则 $T_s = 284.8 \text{ K}$, $T_a = 250.9 \text{ K}$ 。可见, 大气层的存在使地面平衡温度高于全球的有效温度, 同时大气层的平均温度却低于有效温度 T_e
- 当 A_l 加大时, 地面平衡温度也将升高。大气中对长波辐射吸收的主要气体是水汽、二氧化碳、臭氧等。这些气体的含量增加, 将使 A_l 加大, 从而导致地面增温 (温室效应增强)
- 当 A_l 加大时, 大气平衡温度变化复杂 (为什么?)

“大气+地表” 辐射平衡



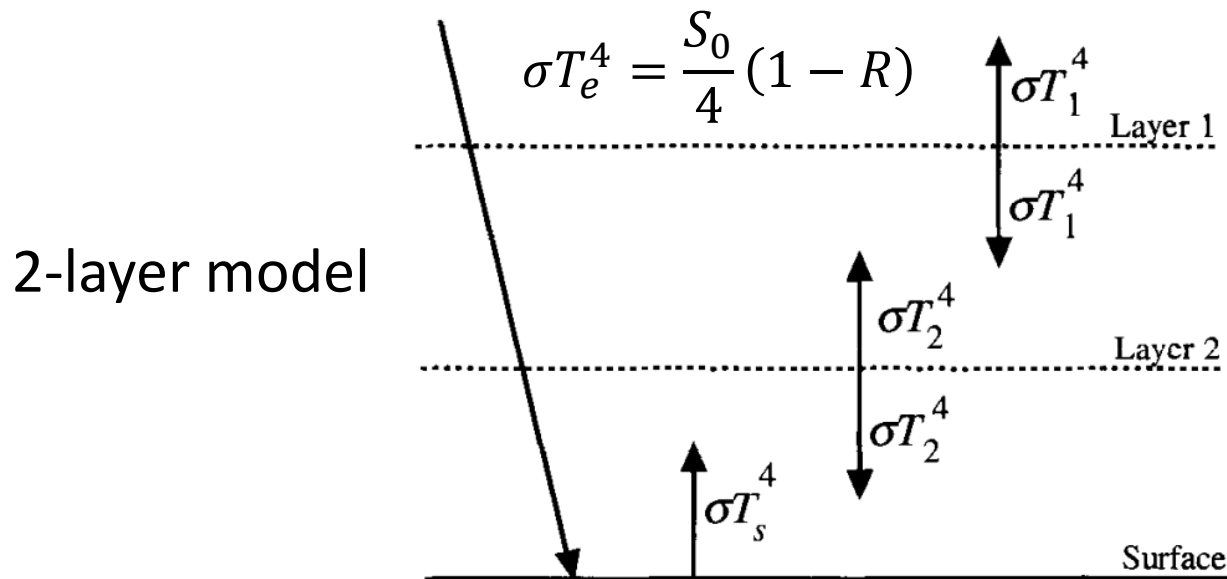
Multi-layer Atmosphere in Radiative Equilibrium

If the atmosphere is divided into multiple layers

Each layer is opaque (black body) for long wave radiation

Each layer is transparent for solar radiation (ignore O_3)

We can get surface and air temperatures as follows, assuming the Earth is in radiative equilibrium.



Multi-layer Atmosphere in Radiative Equilibrium

TOA:
$$\frac{S_0}{4}(1 - R) = \sigma T_e^4 = \sigma T_1^4$$

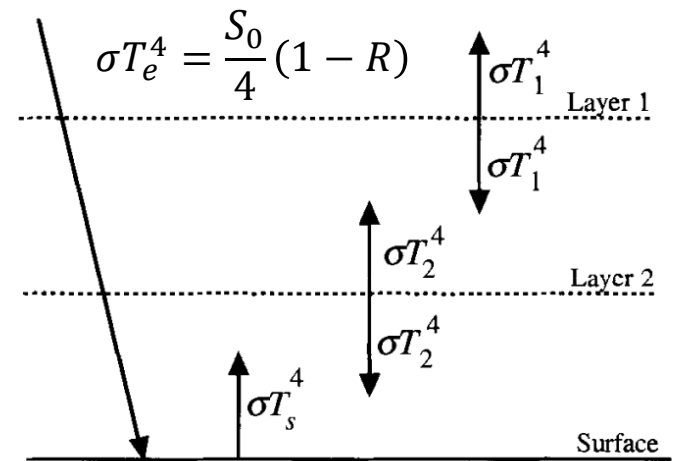
Layer 1:
$$\sigma T_2^4 = 2\sigma T_1^4$$

Layer 2:
$$\sigma T_1^4 + \sigma T_s^4 = 2\sigma T_2^4$$

Surface:
$$\frac{S_0}{4}(1 - R) + \sigma T_2^4 = \sigma T_s^4$$

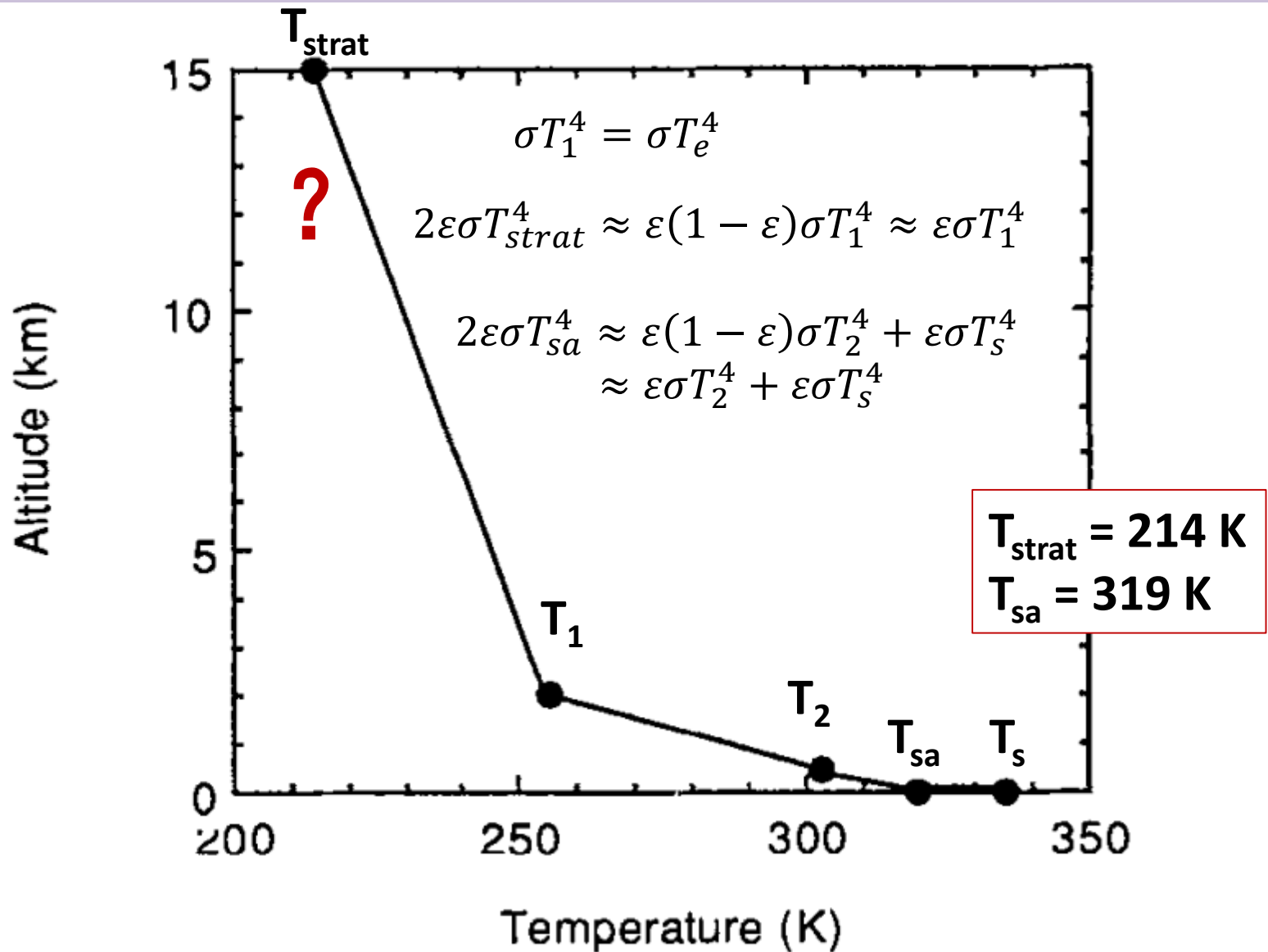
We get:
$$T_s = \sqrt[4]{\frac{3S_0(1 - R)}{4\sigma}} = \sqrt[4]{3}T_e$$

For a n-layer model:
$$T_s = \sqrt[4]{n + 1}T_e$$



Dennis Hartmann book

Multi-layer Atmosphere in Radiative Equilibrium



分层大气的净辐射、辐射冷却

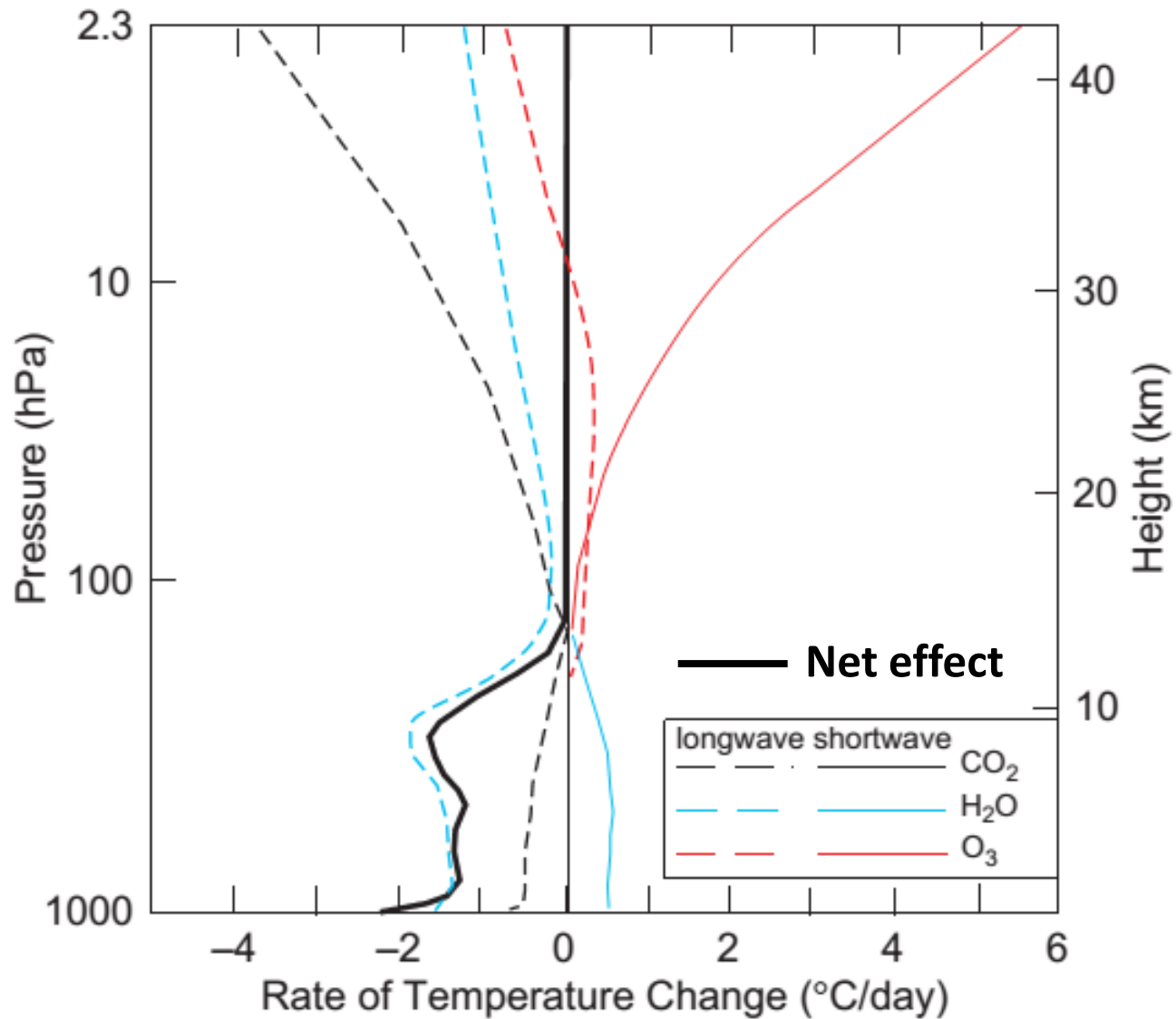
- 对于一薄层大气而言，每一层大气由于太阳辐射和长波辐射的变化而出现的加热或冷却可以根据能量守恒原理来确定。
- 取高度为 z 到 $z+dz$ 之间的一薄层大气，其上下边界的净辐射通量密度为 $F(z+dz)$ 和 $F(z)$ 。其单位面积能量变化率为

$$\rho \frac{\delta q}{\delta t} dz = \rho c_p \frac{\partial T}{\partial t} dz = -\frac{\partial F}{\partial z} dz$$

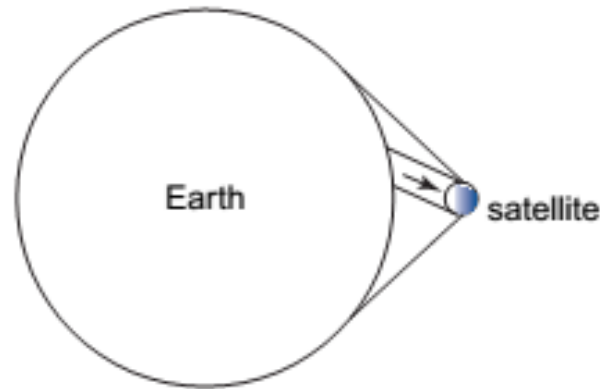
则该层大气温度变化率（单位为 $^{\circ}\text{C}/\text{day}$ ）

$$\frac{\partial T}{\partial t} = -\frac{86400}{\rho c_p} \frac{\partial F}{\partial z}$$

Radiative Heating Rate



思考题



- A. A small, perfectly black, spherical satellite is in orbit around the Earth at an altitude of 2000 km. What angle does the Earth subtend when viewed from the satellite?
- B. If the Earth radiates as a blackbody at an equivalent blackbody temperature $T_e = 255$ K, calculate the radiative equilibrium temperature of the satellite when it is in the Earth's shadow.

思考题

- A. Consider two opaque walls facing each other. One of the walls is a blackbody and the other wall is “gray” (i.e., α_λ independent of λ). The walls are initially at the same temperature T and, apart from the exchange of radiation between them, they are thermally insulated from their surroundings. If α and ε are the absorptivity and emissivity of the gray wall, prove that $\varepsilon = \alpha$.
- B. Consider the situation where two gray walls are facing each other. One wall has absorptivity α_1 and the other α_2 . Prove that

$$\frac{F'_1}{\alpha_1} = \frac{F'_2}{\alpha_2}$$

where F'_1 and F'_2 are the flux densities of the radiation emitted from the two plates. Make sure of the fact that the two plates are in radiative equilibrium at the same temperature.

温室效应、温室气体

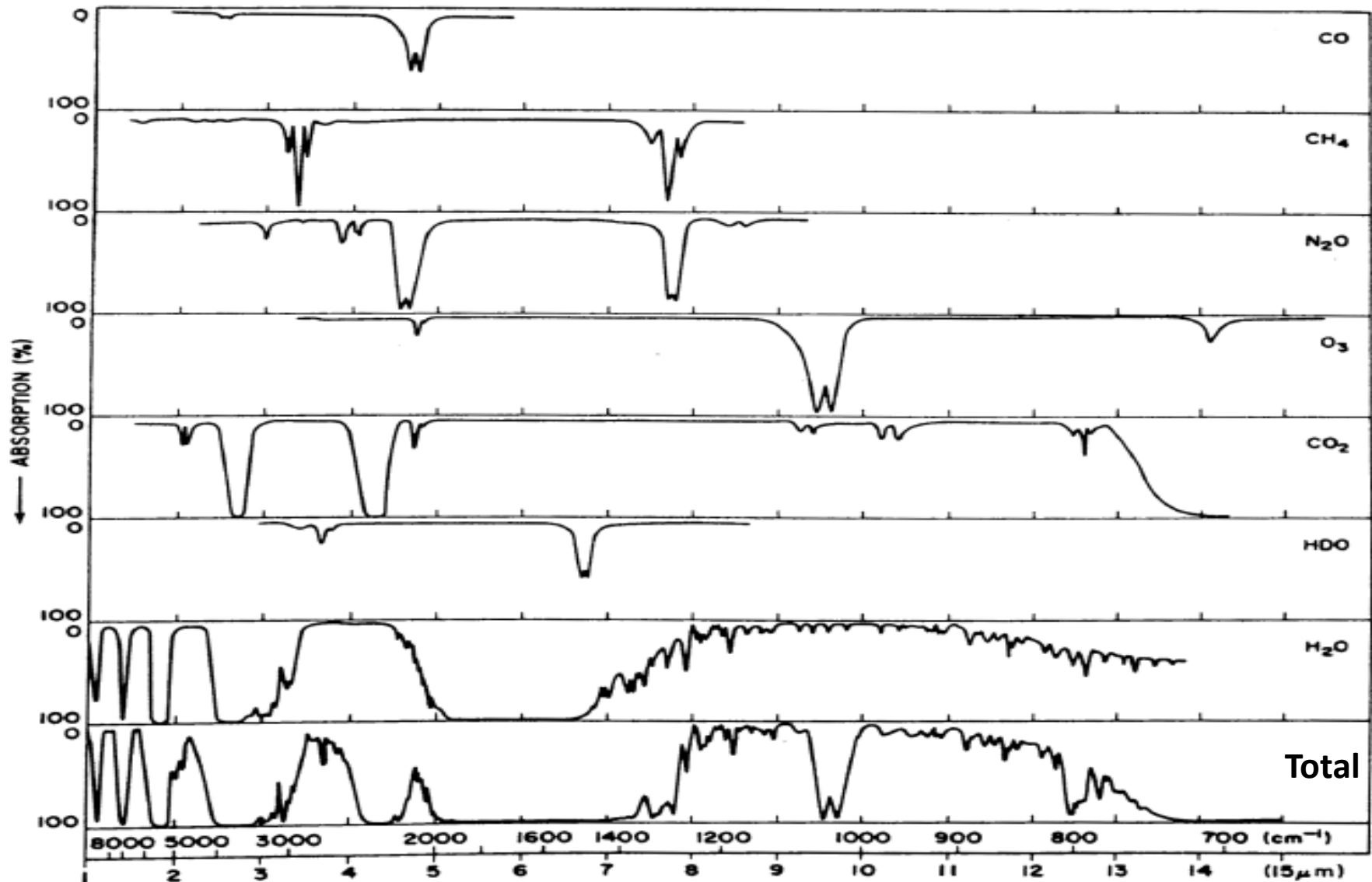
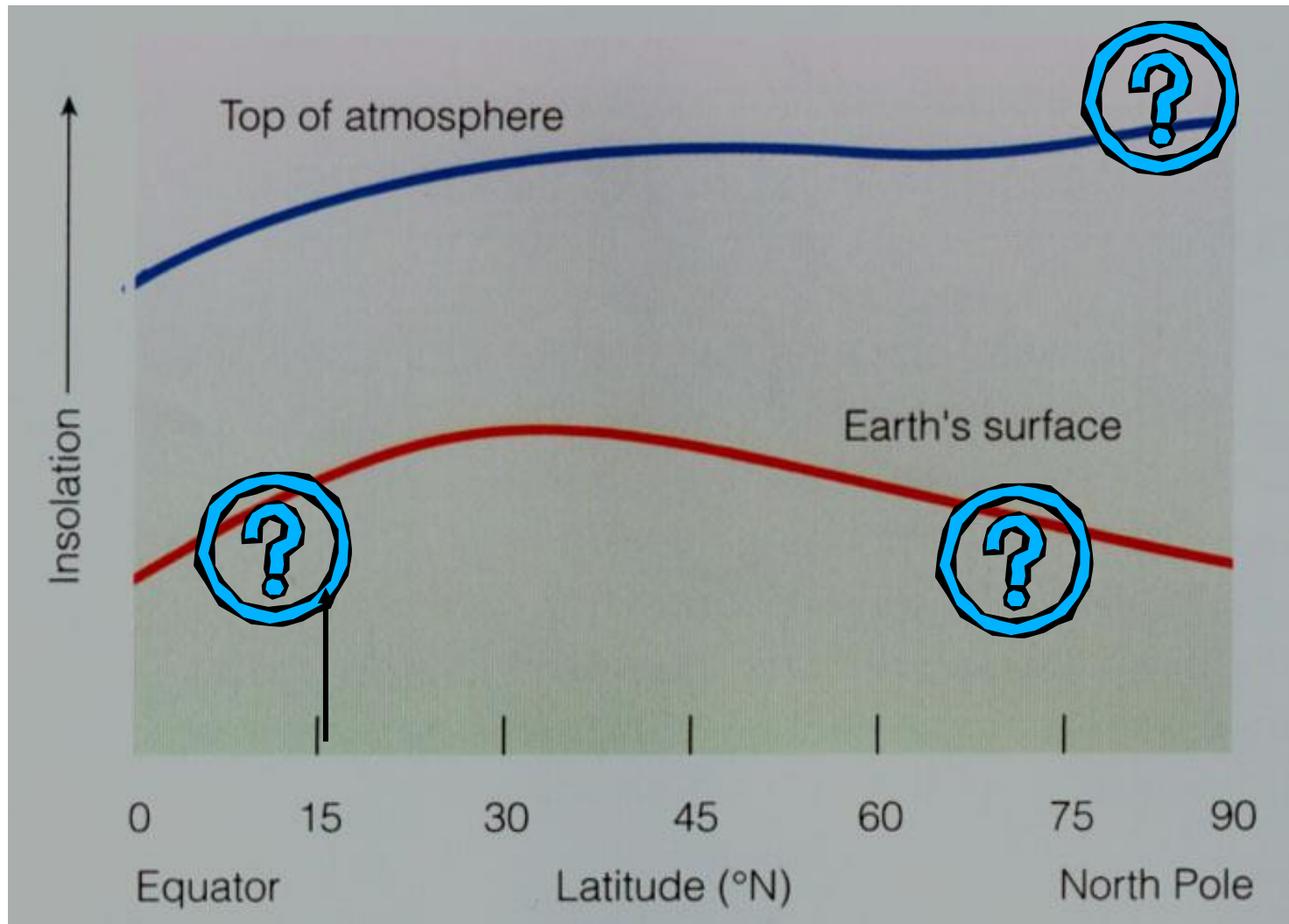


Figure 7.3 Low-resolution IR absorption spectra of the major atmospheric gases.

Incident Solar Radiation on Summer Solstice



地球系统辐射平衡

地气系统的有效温度取决于二个因子

- 太阳常数：主要由太阳温度和日地平均距离决定。
- 地气系统的行星反照率：它与地气系统的许多特性，如海洋的反射、陆面的反射、大气散射和云反射有关。

在太阳系中，几颗行星距太阳的距离不同，它们收到的太阳辐射的情况也不同。

- 下表给出地球及其相邻的五颗行星离太阳的距离和它们相应的太阳常数。
- 假设它们的行星反照率均为 $A = 0.3$ ，它们的有效温度都各自是多少？在表中也给出目前已测到的各颗行星的行星反照率。请进一步计算它们各自的有效温度。